Research on Rotorcraft Aerodynamics and Aeroacoustics at DLR

Thorsten Schwarz

DLR, Institute of Aerodynamics and Flow Technology
Braunschweig, Germany

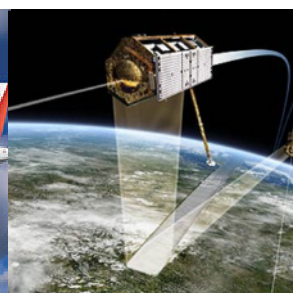
Lecture at JAXA
November, 10th, 2017
Tokyo, Japan

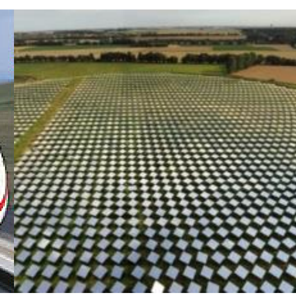
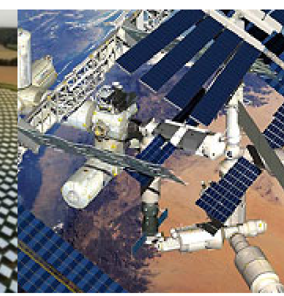
Outline

- Helicopter Research at DLR
- Numerical Simulation of Helicopter Aerodynamics
- Numerical Optimization of Helicopters
- Helicopter Low Noise Flight Procedures
- Measurement Techniques for Helicopters
- Wind Turbine Simulation
- Conclusion

DLR – German Aerospace Center

- National Research Institution
    - Aeronautics
    - Space Research and Technology
    - Transport
    - Energy
    - Defence and Security
- Space Administration
- Project Management Agency


DLR

Locations and employees

Approx. 8000 employees across
33 institutes and facilities at 20 sites.

Offices in Brussels, Paris,
Tokyo and Washington.

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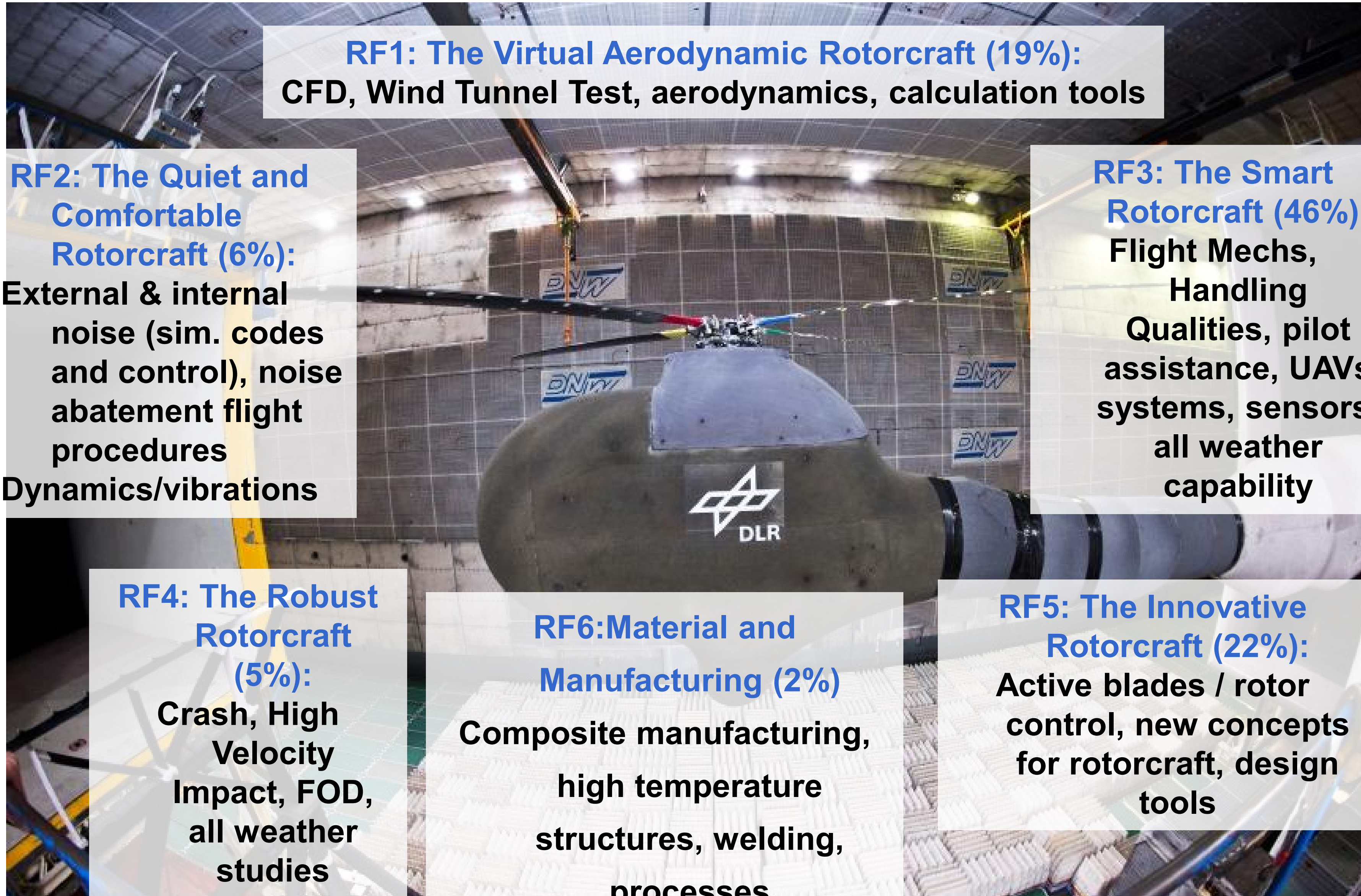
Rotorcraft Research Fields (RF) (activity percentages 2015)



RF1: The Virtual Aerodynamic Rotorcraft (19%):
CFD, Wind Tunnel Test, aerodynamics, calculation tools

RF2: The Quiet and Comfortable Rotorcraft (6%):
External & internal noise (sim. codes and control), noise abatement flight procedures
Dynamics/vibrations

RF3: The Smart Rotorcraft (46%):
Flight Mechs, Handling Qualities, pilot assistance, UAVs systems, sensors, all weather capability

RF4: The Robust Rotorcraft (5%):
Crash, High Velocity Impact, FOD, all weather studies

RF6:Material and Manufacturing (2%)
Composite manufacturing, high temperature structures, welding, processes

RF5: The Innovative Rotorcraft (22%):
Active blades / rotor control, new concepts for rotorcraft, design tools

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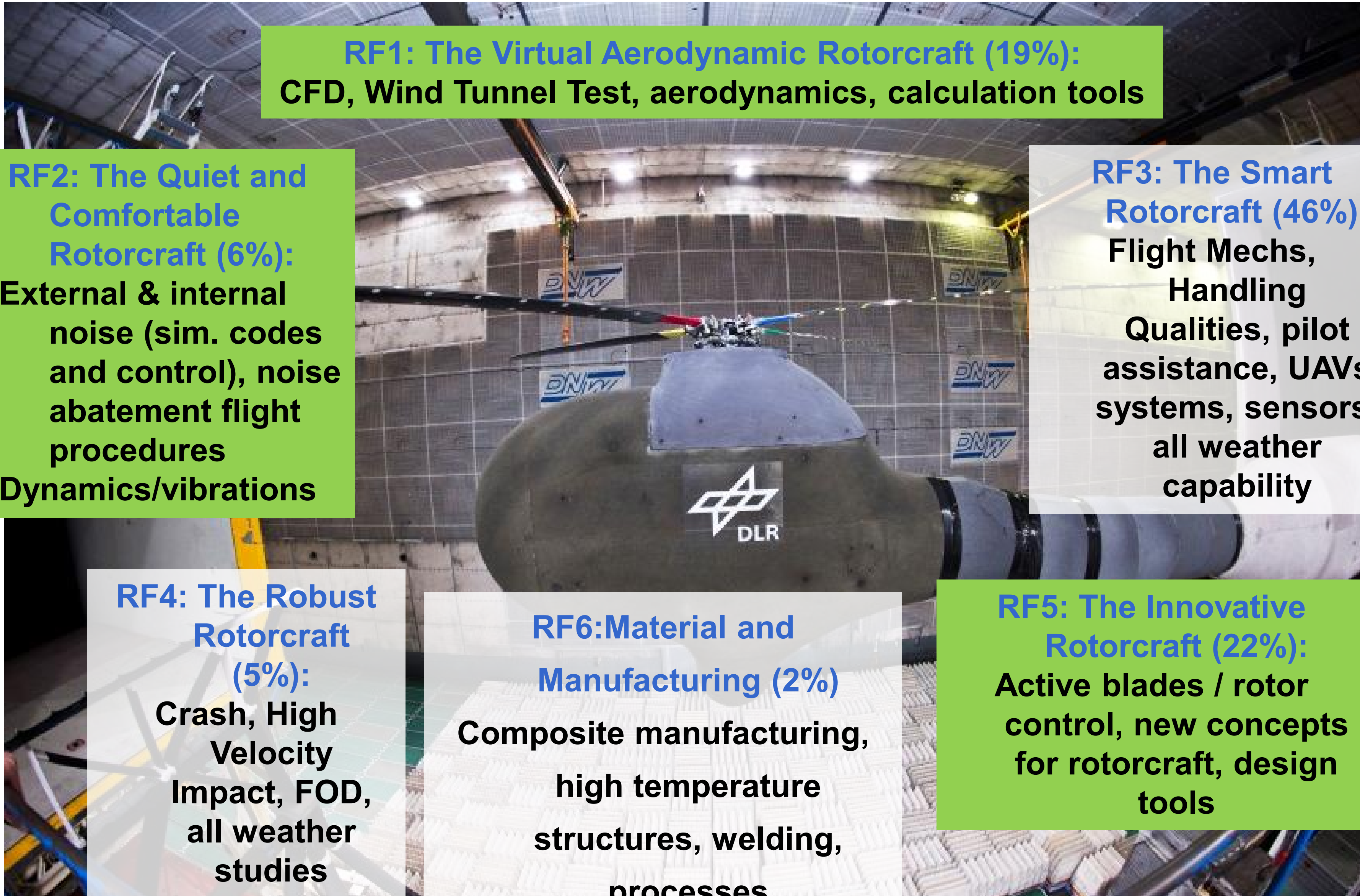

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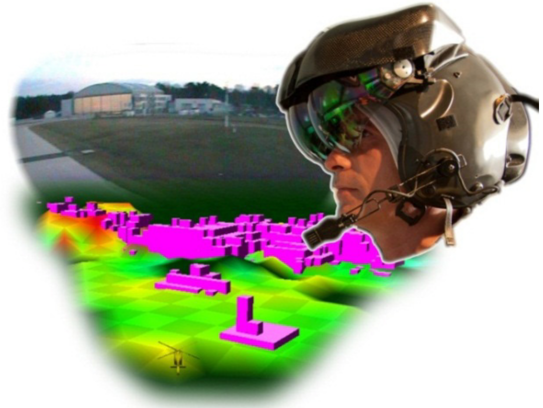
DLR Rotorcraft **Research Facilities**

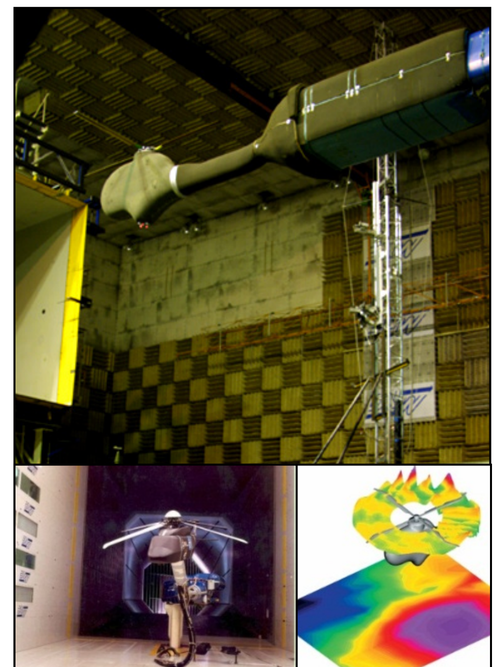
EC 135 – Inflight Helicopter Simulator



Helmet Mounted Display

High Performance Computing

H/C Research Simulator



Rotor Test Facility for DNW-LLF

DLR

Institute of Aerodynamics and Flow Technology

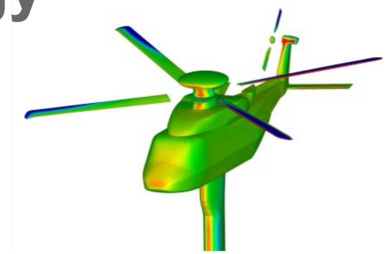
Department Helicopters – Research Focus:

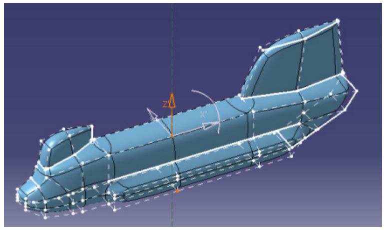
Braunschweig (Head: Thorsten Schwarz)

- Numerical prediction of rotorcraft aerodynamics and aeroacoustics
- Multidisciplinary design and optimization
- Pre-Design
- Development of noise abatement flight procedures
- Simulation and design of wind turbines

Göttingen (Head: Markus Raffel)

- Experimental and numerical research for physical phenomena
- Active and passive flow control
- Development of optical measurement techniques for helicopters
- Noise footprint prediction and noise impact of fixed wing aircraft





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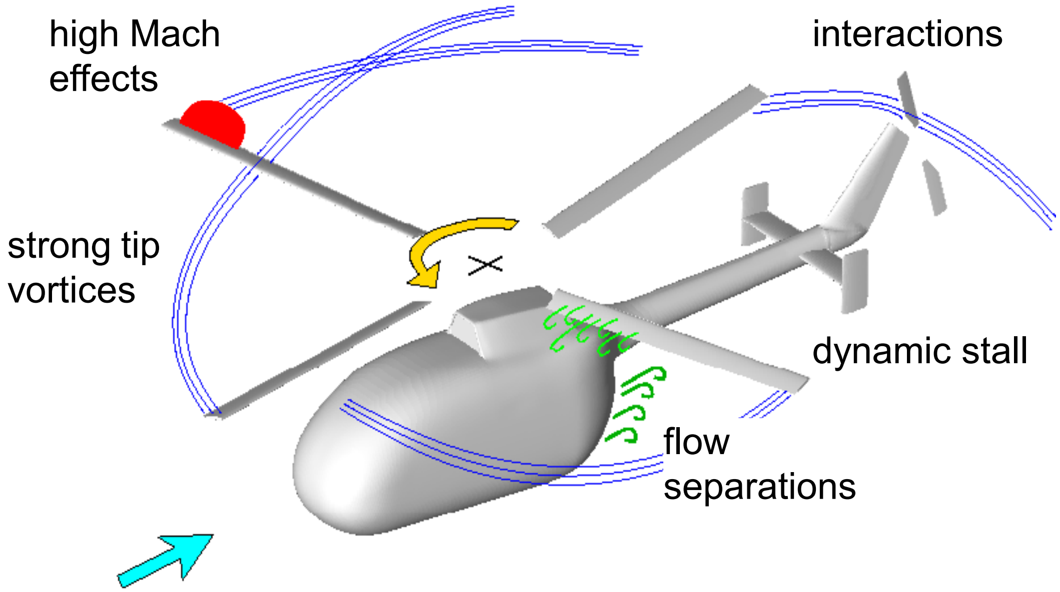
Aerodynamics of the Helicopter



Phenomena affect

- performance
- loads
- vibrations
- noise

⇒ CFD most accurate prediction method

⇒ CFD has to be adapted to the specifics of rotorcraft

CFD solver FLOWer

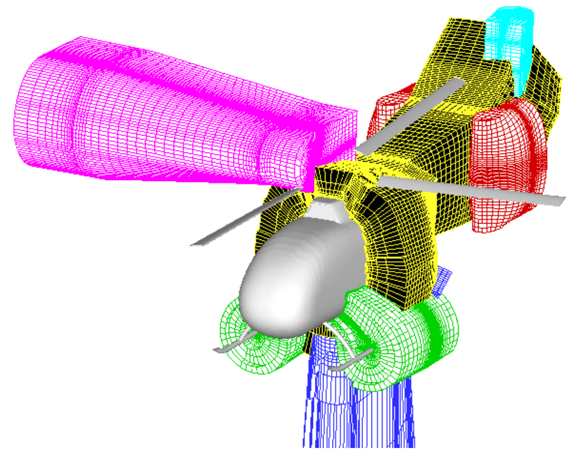
URANS solver for structured grids

- first large scale flow solver of DLR (in use since 1995)

  → well adapted code for Helicopters

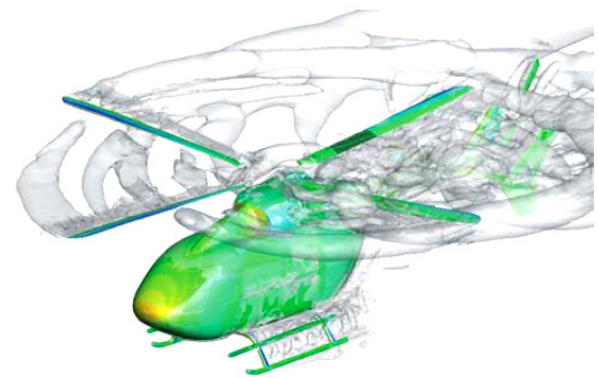
  under development until 2016

  reference code for future CFD developments



Features

- finite volume discretization
  - 2^{nd} order central/upwind discretization
  - 4^{th} order PADE scheme
- Runge-Kutta time integration, Dual-time stepping
- implicit residual smoothing, multigrid
- 0/1/2/7-equation turbulence models
- overset grids, deforming grids



- applied by Airbus Helicopters for analysis of rotors and complete helicopter

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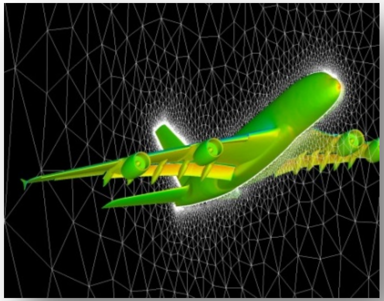
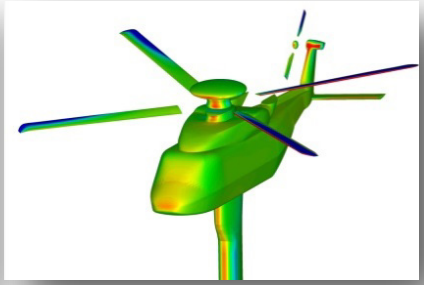
CFD Solver TAU

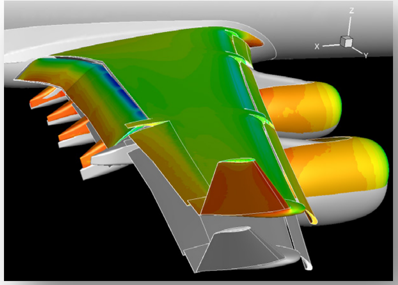
- URANS solver for hybrid, unstructured grids
- Finite Volume method 2nd order
- Advanced turbulence models, e.g. RSM
- Hybrid RANS/LES
- overset grids, mesh deformation, adaptation
- Linearized solver, adjoint solver
- Interfaces for multidisciplinary coupling

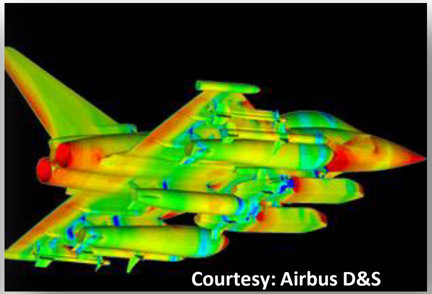
- Applied in European aircraft industry,
  e.g. Airbus, Airbus D&S, Airbus Helicopter, RRD, …)
- Research platform for European universities
  and research organizations

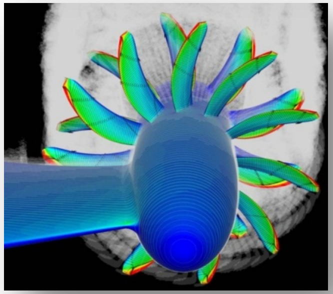
→ large scale use for fixed wing aircraft since 2006
→ helicopter rotor simulation capability since 2014
→ ongoing validation activities for helicopters

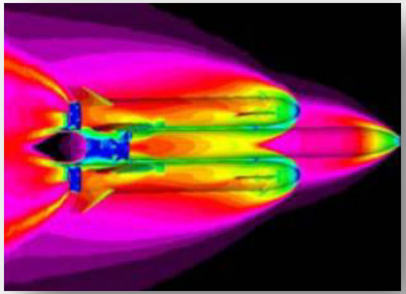












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Coupling CFD with Flight Mechanics

- Rotor controls ("pilot inputs") have to be trimmed to desired flight state
- large blade motion due to blade dynamics and elastic deformations
- FLOWer and TAU are coupled with HOST from Airbus Helicopters
- Coupling method: periodic coupling
  (= loose coupling, weak coupling or delta airloads coupling)

HOST

- Blade Element Aero + corrections by CFD
- Rotor Trim (Θ)
- Blade Dynamics (β, ζ)
- elastic Deformation

FLOWer / TAU

- Grid Deformation
- Flow Computation
- Rotor-Loads

Blade motion

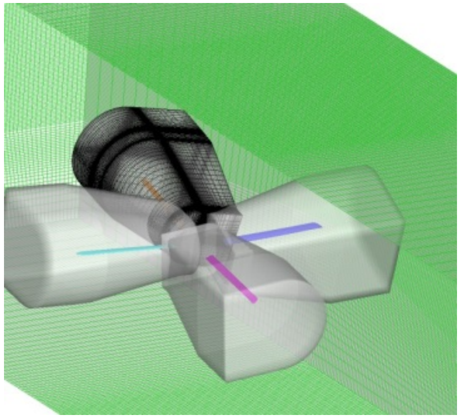
Aero Loads

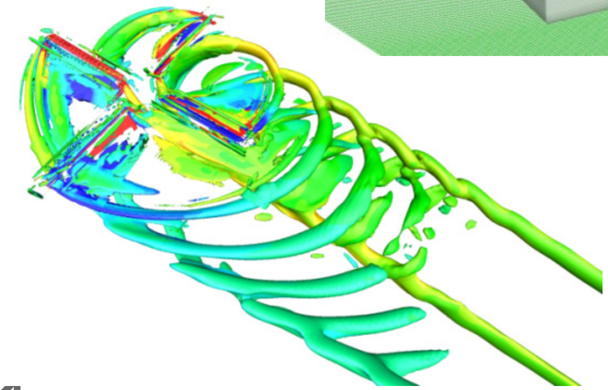

BO105 hingeless rotor

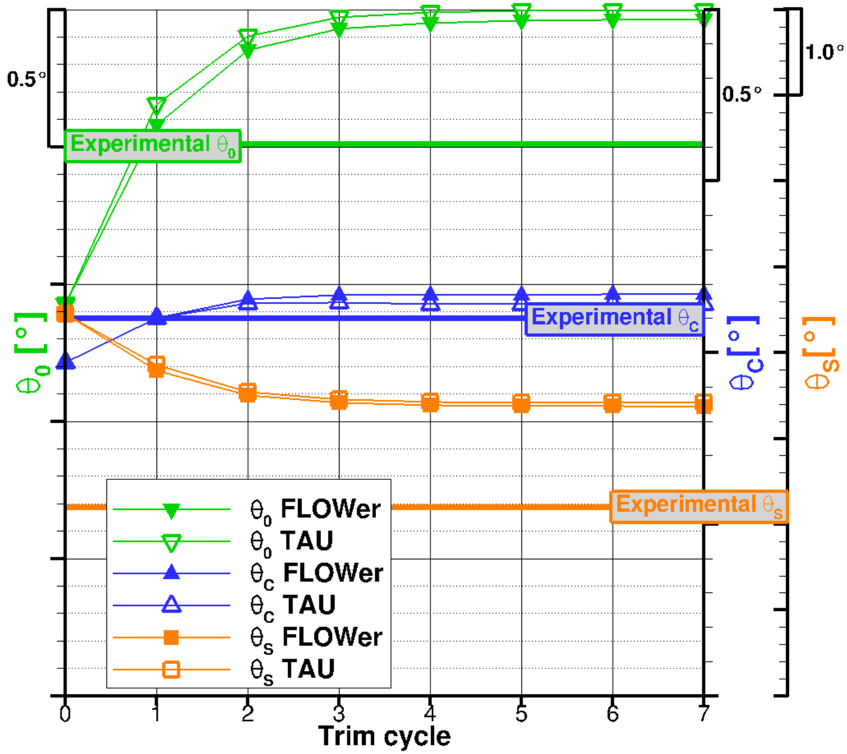
Fluid-Struktur-Trim-Coupling

Example: ONERA 7AD-Rotor

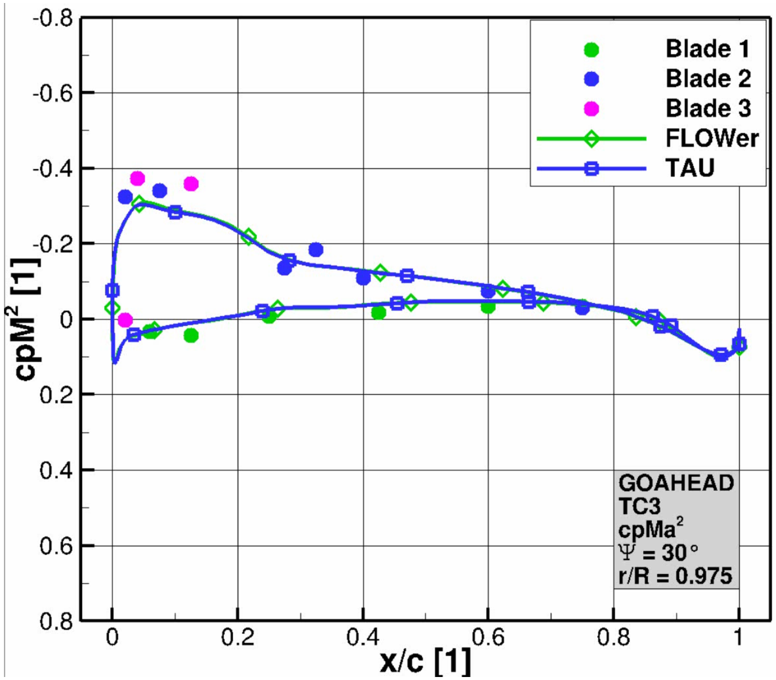
- Flow Conditions: M = 0,204, M_{Tip} = 0,617
- Hexahedral grid: ~6.2 million points
- Excellent agreement between TAU and FLOWer

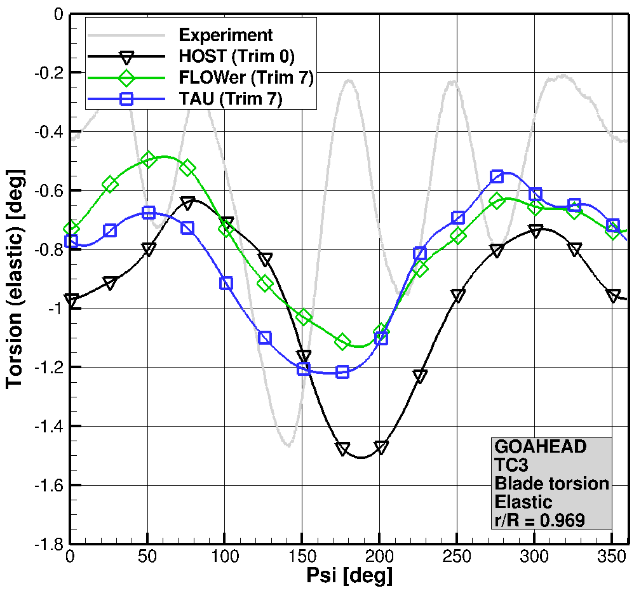






Fluid-Structure Coupling - Isolated 7AD Mainrotor
Blade pressures and dynamics





Elastic Torsion at r/R = 0,969

- Good Agreement between FLOWer and TAU
- Differences due to missing interference effects of fuselage
- 5/rev frequency content of the elastic torsion not present in the simulations

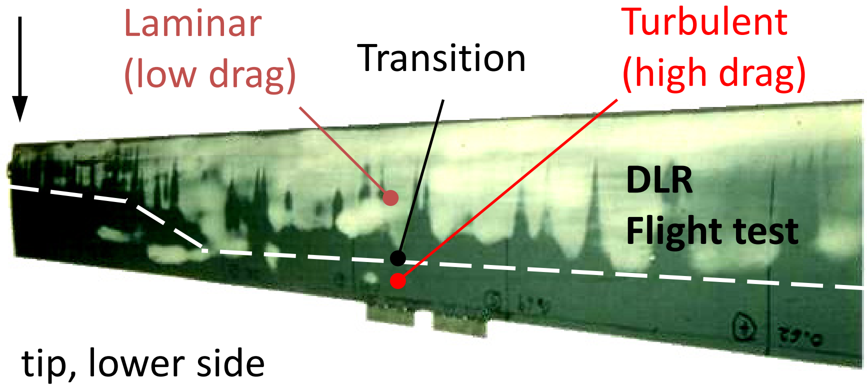
Transition Prediction for Rotors

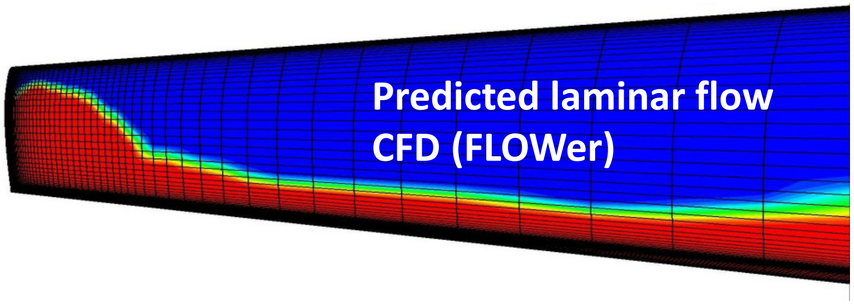
BO 105 Blade (Hover)

- Laminar flow reduces power requirement of rotors
- Transition mechanisms need to be identified
- Impact on rotor power to be quantified

Approach
- Coupling of CFD with boundary layer method and empirical transition criteria
  - Tollmien-Schlichting
  - Cross-Flow instabilities
  - Attachment Line Transition
  - Bypass-Transition

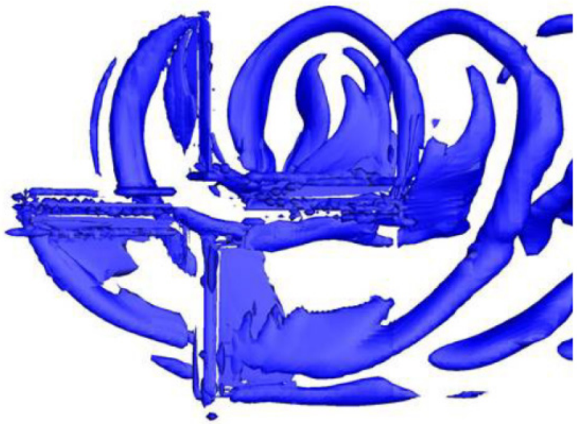
- Implemented in FLOWer and TAU

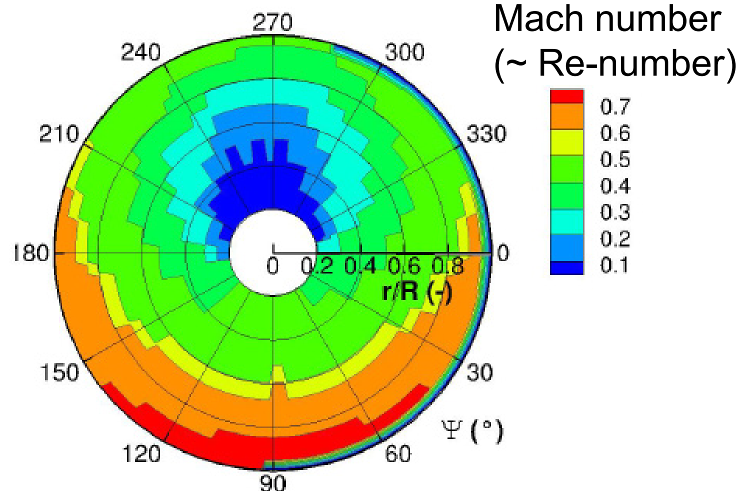


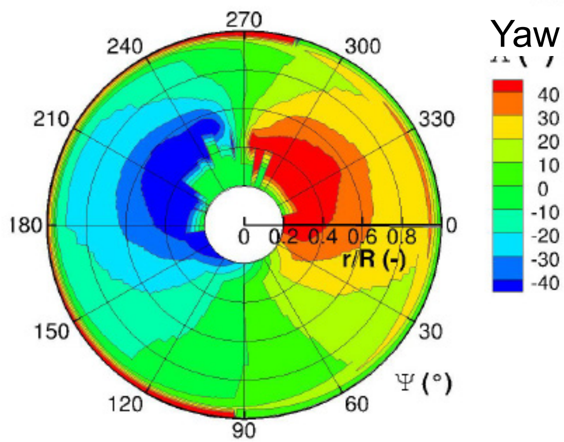


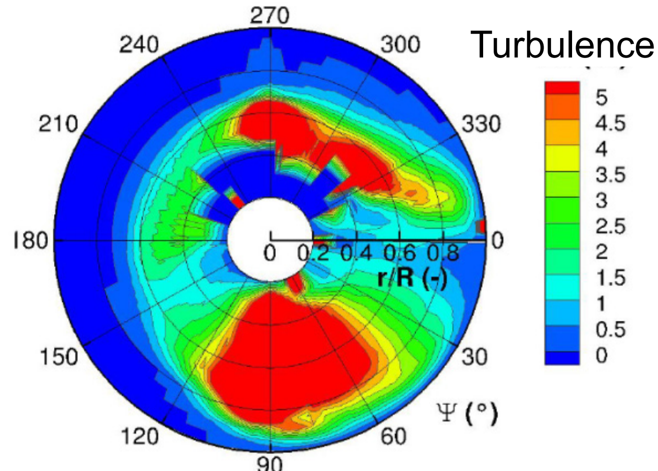
Transition Prediction for Rotors

Example: 7AD-Rotor in fast forward flight , μ=0,42









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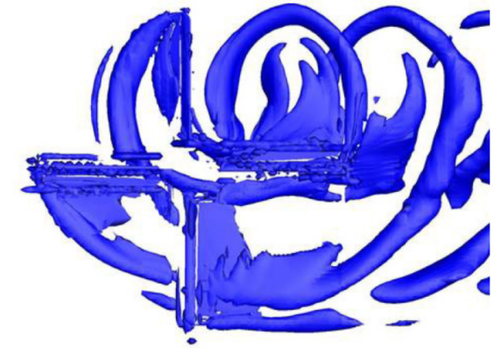
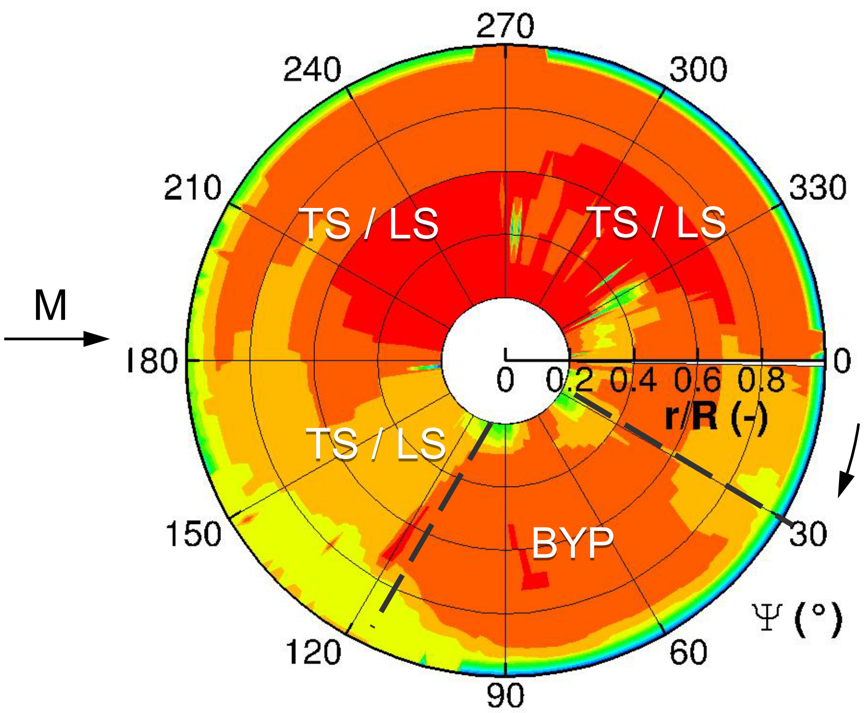
Transition on a rotor in fast forward flight

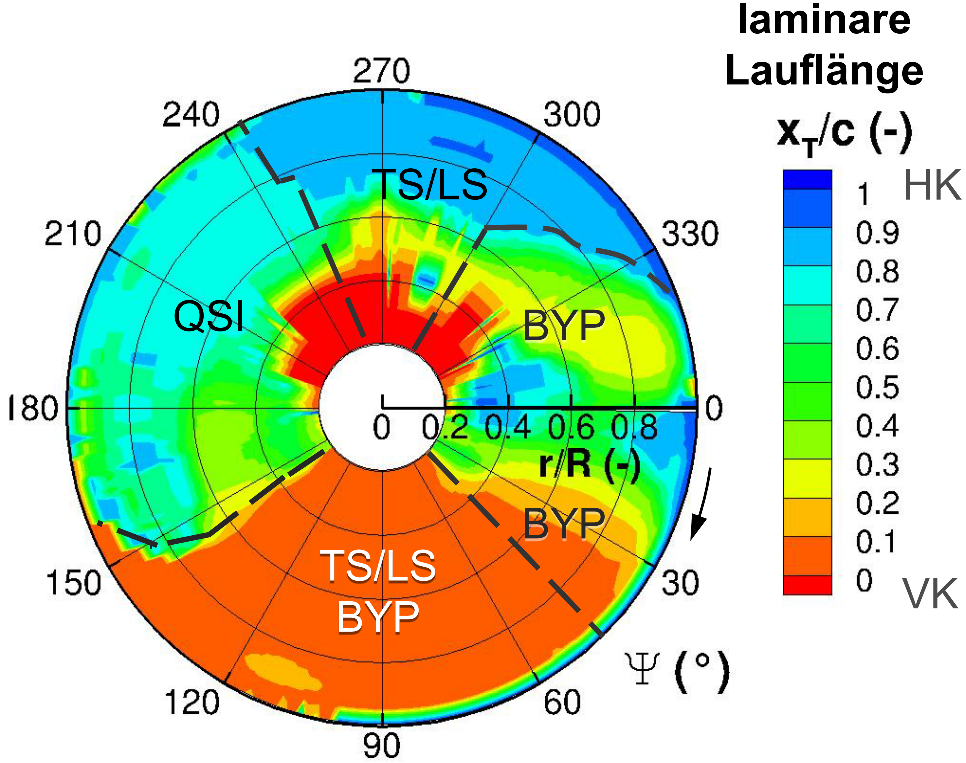
- Varying inflow has significant impact on transition mechanism and extend of laminarity
- power: -3,7% , thrust: +1,4%



Upper side of rotor



Lower side of Rotor



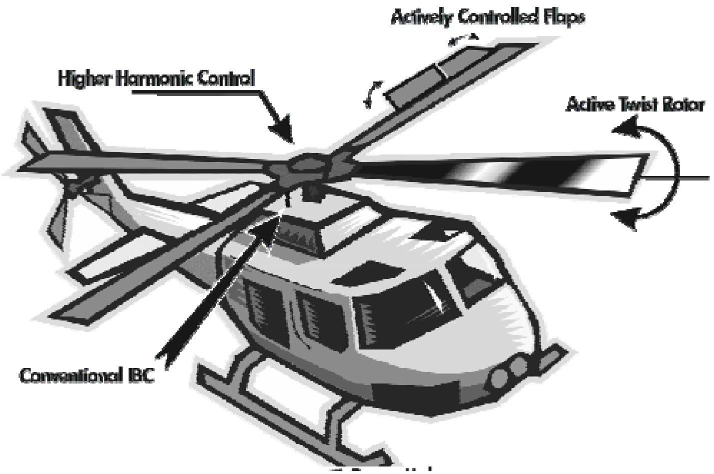
TS: Tollmien-Schlichting, LS: Laminar Separation, QSI: Cross-Flow Instabilities, BYP: Bypass, ALT: Attachment Line Transition

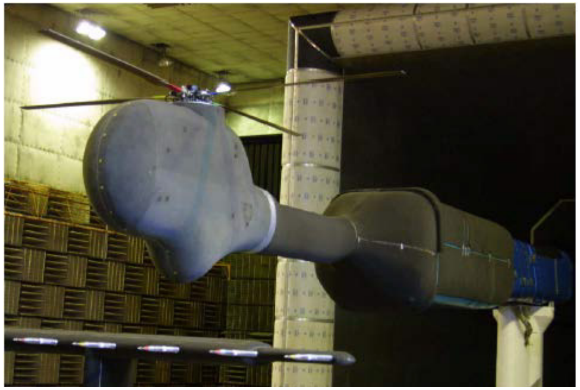
Validation for Active rotors

- Actives rotor have actuators allow higher harmonic control
    - higher harmonic blade pitch angle (HHC/IBS)
    - active twist
    - blade flaps
- Active Rotors have a great potential to reduce noise and vibrations, and to increase performance

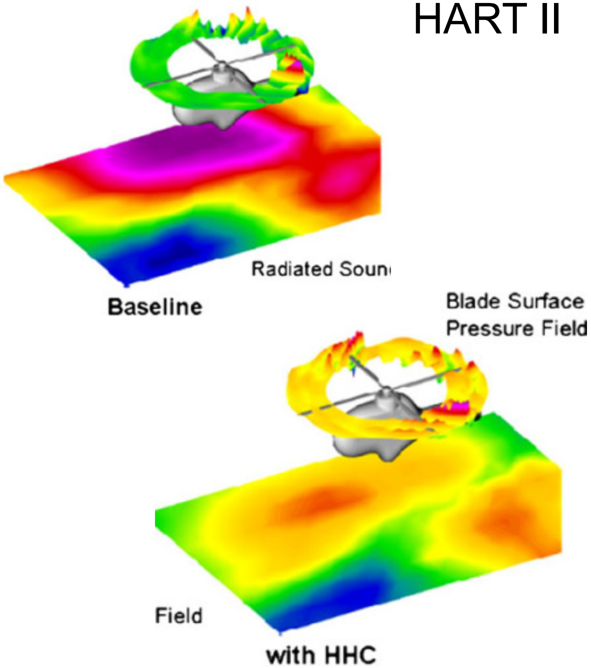
- Higher Harmonic Control (HHC):
  Pitch = Pilot-Control input plus HHC:

$$\theta = \theta_0 + \theta_{1c} \cos \Psi + \theta_{1s} \sin \Psi + \theta_3 \cos(3\Psi - \Delta\Psi)$$





HART II



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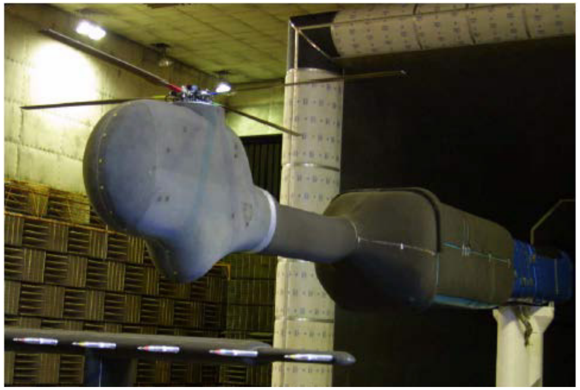
DLR-JAXA Cooperation from 2010 – 2016

- Objective: improve knowledge and tools for advanced active rotor technologies
- Common Test Case: HARTII experiment (Higher Harmonic Control Aeroacoustic Rotor Test)
- Validation by cross comparison of CFD-results
  - DLR: CFD-solvers FLOWer, TAU
  - JAXA: rFlow3d



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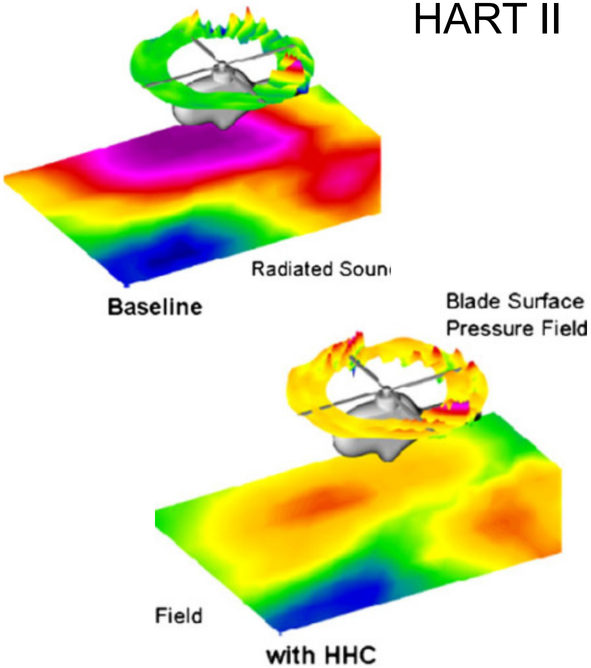
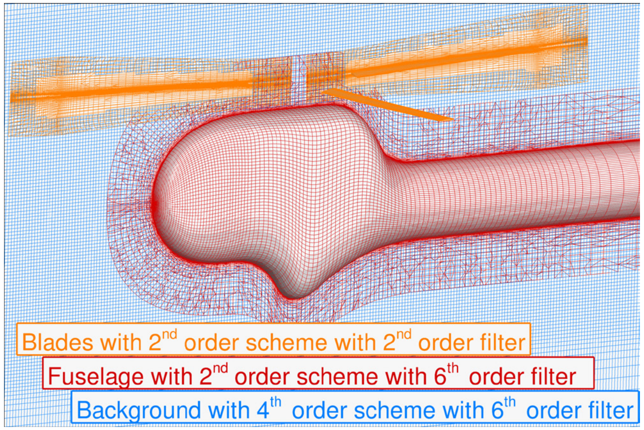
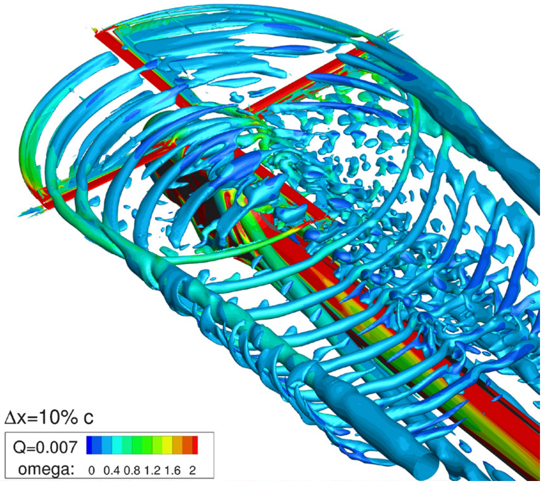


DLR: FLOWer - Increased prediction accuracy

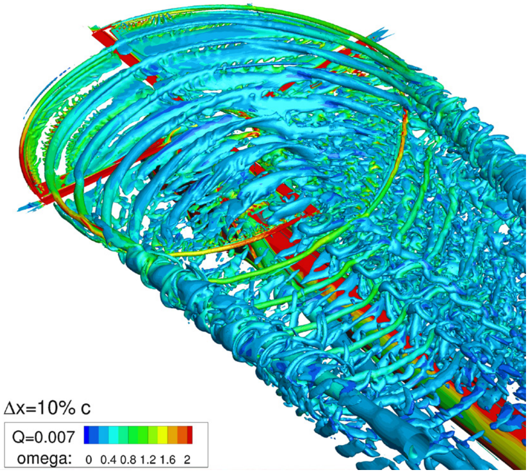
- Implement 4th order accurate PADE-scheme in structured FLOWer code
- simulation of HART II BL case on grid with 103 million cells (grid resolution 0.1 chord)
- Fluid-Structure-Trim Coupling with HOST
- Acoustic peaks greatly improved with 4th order mesh in contrast to 2nd order
- Amplitude of BVI-Peaks similar to experiment



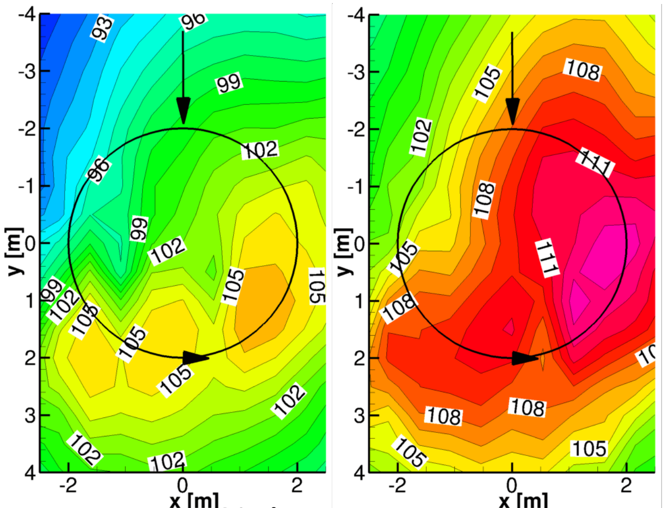
Mesh for HARTII test



2nd order accurate



4th order accurate

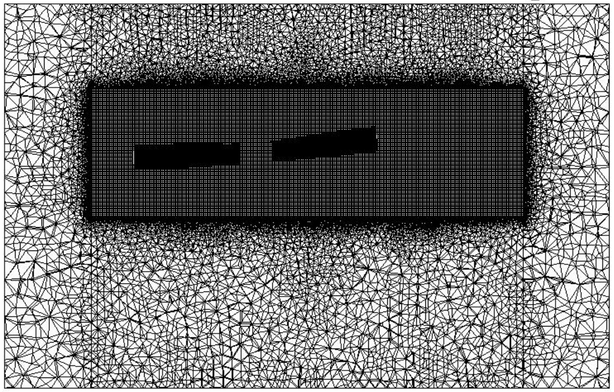


Noise carpets

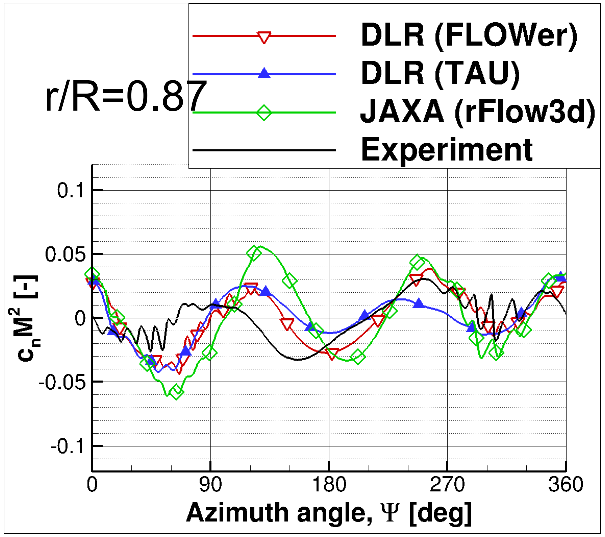
left/right: 2nd/4th order accurate

DLR-JAXA-co-operation
TAU – Fluid-Structure-Trim coupling for Active Rotors

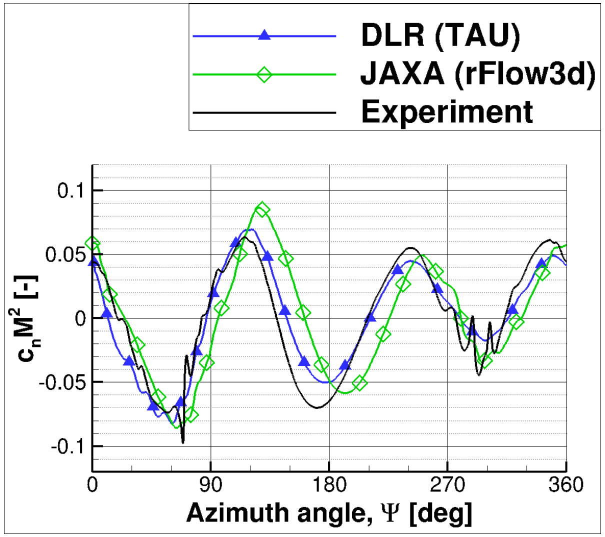
- Extend Fluid-Structure-Trim coupling for Higher-Harmonic-Control (HHC)
- Simulation of HART II test cases with 2nd order accurate TAU solver
  - Baseline case
  - Minimum Noise case
  - Minimum Vibration case



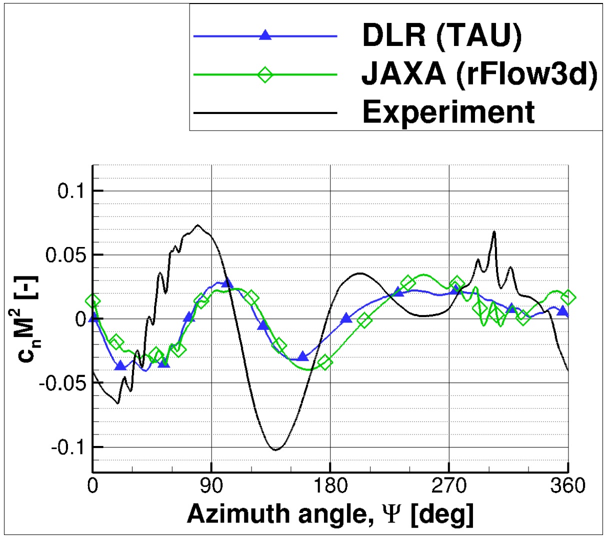
computational grid



Baseline case



Minimum Noise case



Minimum Vibration case

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Challenges in Rotor Optimization

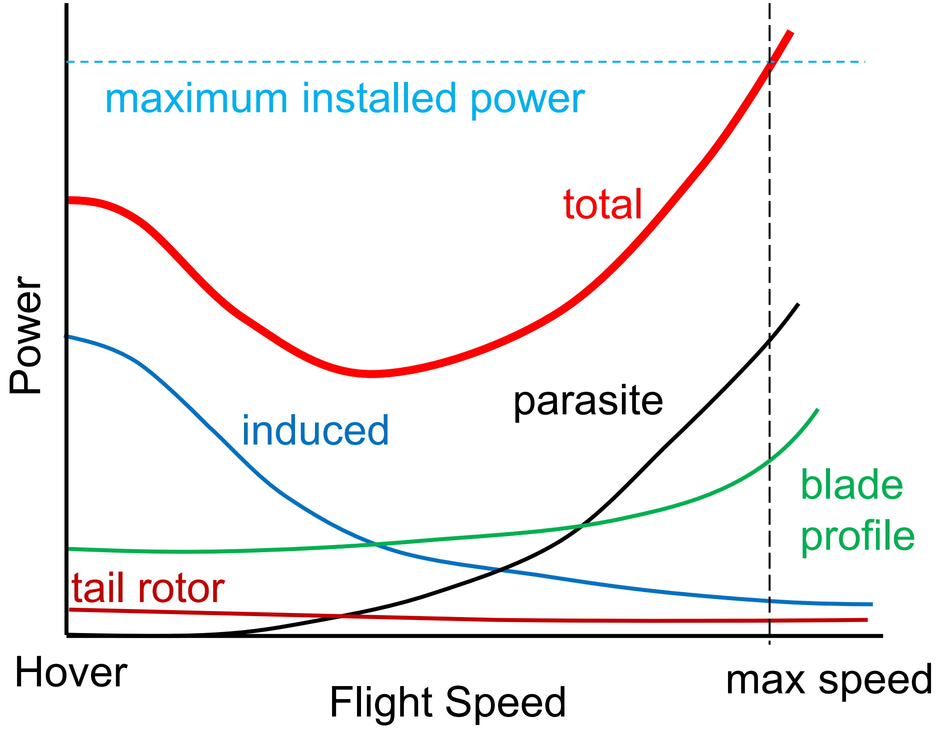
Simulation Challenges:

⇨ complex low field needs to be resolved
⇨ Fluid-Structure-Trim Coupling mandatory
⇨ Excessive simulation times: Single rotor simulation about 1 week on 24 cores

Optimization Challenge:

- Small number of design parameters
- Multipoint Optimization: Hover, Forward Flight

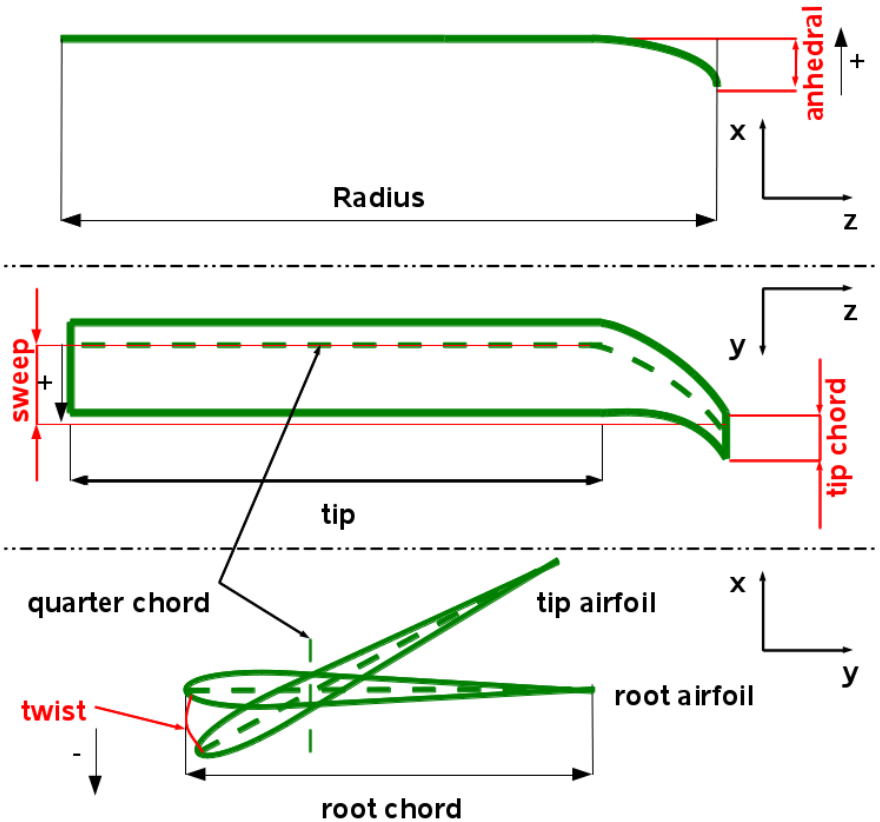
⇨ Multi-Point Surrogate based optimization



Rotor design parameters

Design parameters

- Twist
- Chord
- Anhedral
- Sweep



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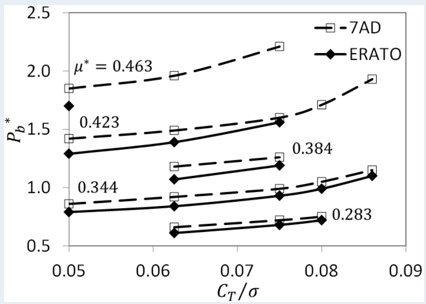
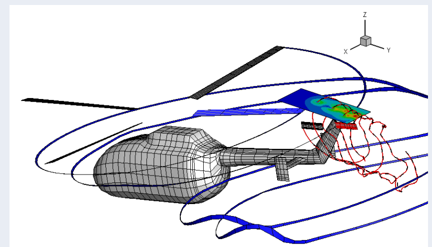
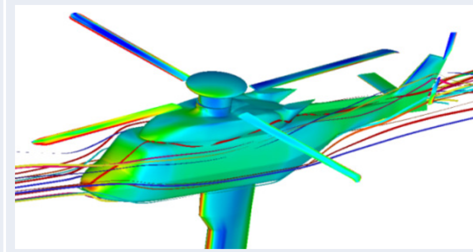
Helicopter aerodynamic prediction tools

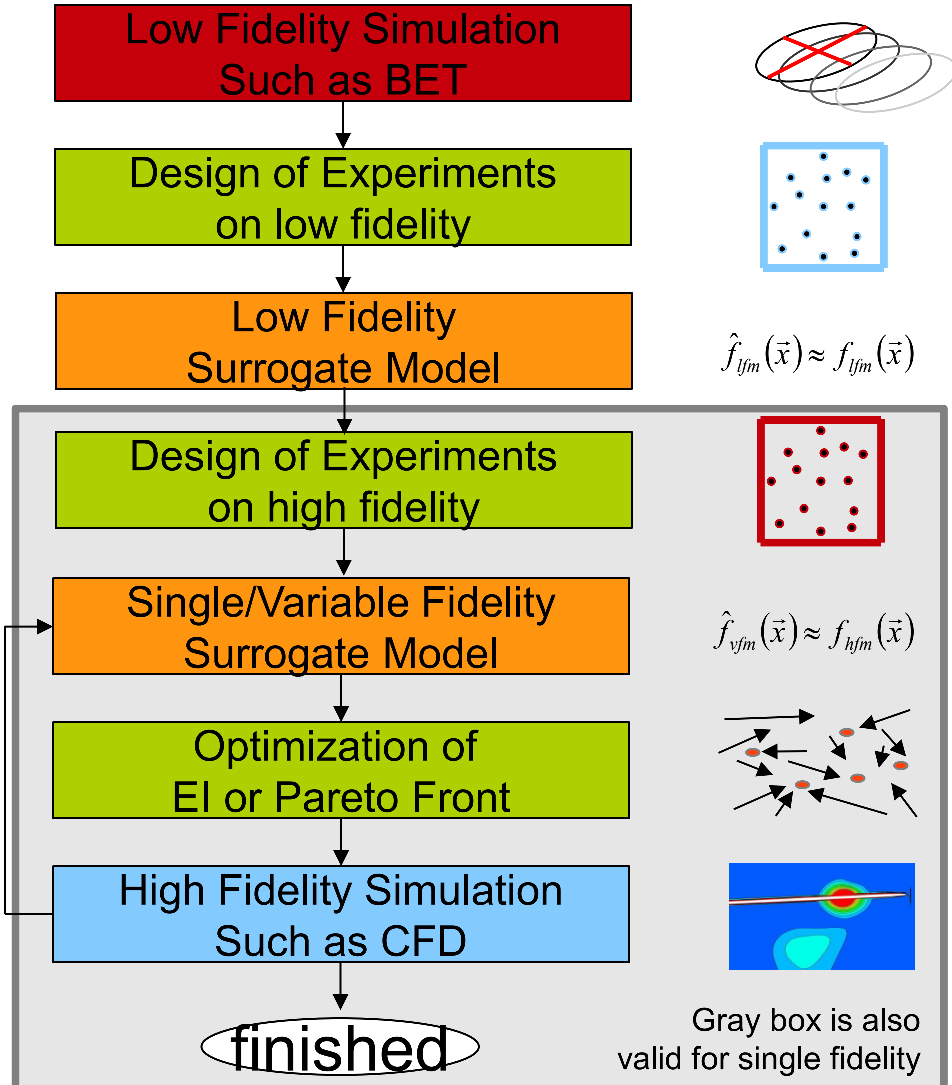
Fidelity	Low Fidelity	Mid Fidelity	High Fidelity
Model	Momentum or Blade Element Theory	Free-Wake Panel Methods	uRANS (CFD)
			
Use	Performance Flight mechanics	Interference effects Risk mitigation	Detailed analysis Optimization
Method	HOST*, S4	UPM	FLOWer, TAU

Accuracy: global (with tuning) → interferences → all physics

Speed: seconds ← minutes / hours ← hours / days

** Airbus Helicopter code*

Multipoint Variable Fidelity Optimiztion



Single Fidelity Optmization

- Universal Kriging

$$\hat{y}(\vec{x}) = f(\vec{x})_{poly} + \varepsilon(\vec{x})$$

Variable Fidelity Optimisation

- Hierarchical Kriging

LoFi:

$$\hat{y}_{LFM}(\vec{x}) = f(\vec{x})_{poly} + \varepsilon_{LF}(\vec{x})$$

HiFi:

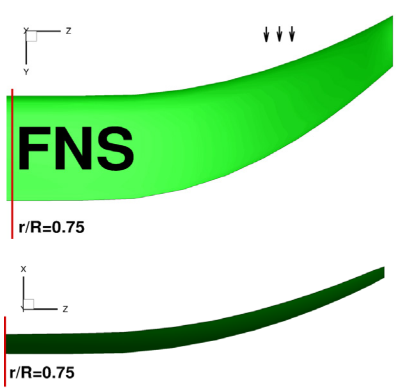
$$\hat{y}_{VFM}(\vec{x}) = \rho\, \hat{y}_{LFM}(\vec{x}) + \varepsilon_{HF}(\vec{x})$$

In-House
Optimization suite

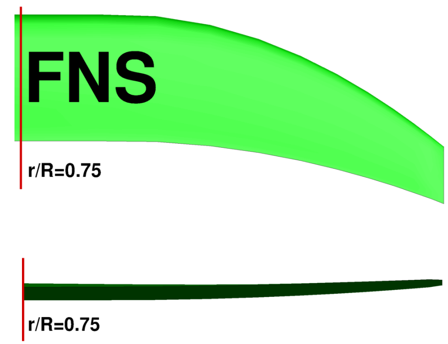
Single Objective Optimization

Rectangular blade (7A-Rotor)
4 Design parameters: twist, anhedral, sweep, tip chord

Flight State	Best Variable Fidelity Method (three levels)	Time saving	Rotor Power reduction
Hover	1. Blade Element + FISUW 2. Euler 3. RANS	42 %	7.1 %
Cruise	1. Prescribed Wake 2. Euler single Blade 3. uRANS	83 %	5.9 %



Hover
optimized

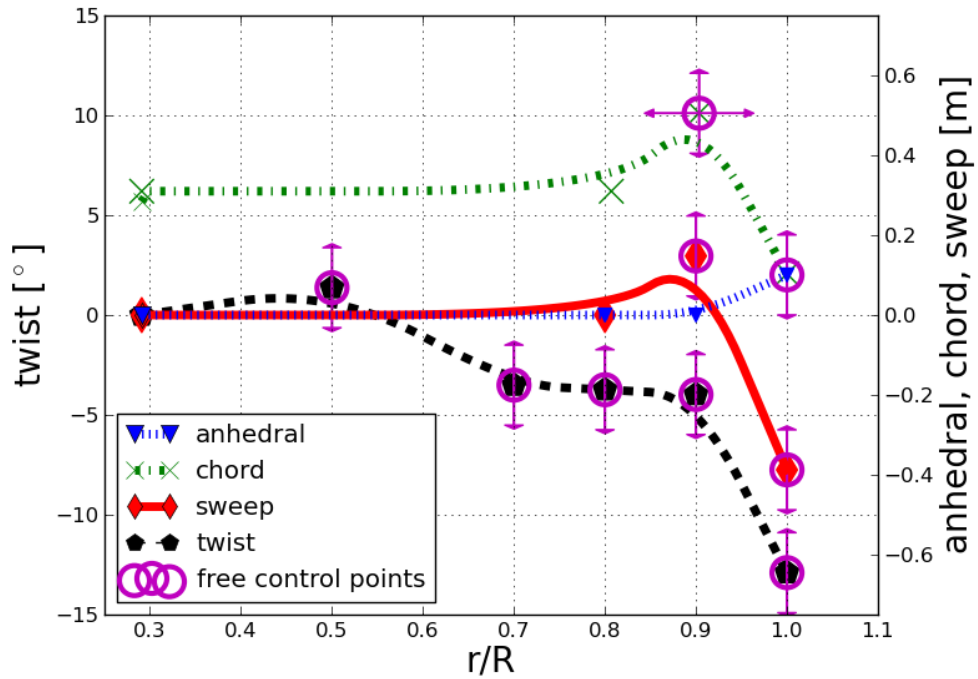


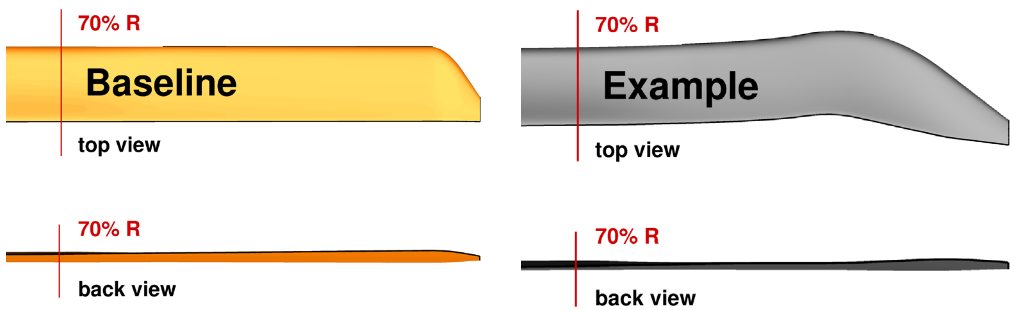
Cruise
optimized

DLR

Application example: five bladed rotor - Parameterization

- 10 design variables
  - Twist (5)
  - Chord (2)
  - Sweep (2)
  - Anhedral (1)
- Parametrization based on NURBS
- Constraint on pitch link loads
- Structural properties of blades adapted by scaling laws

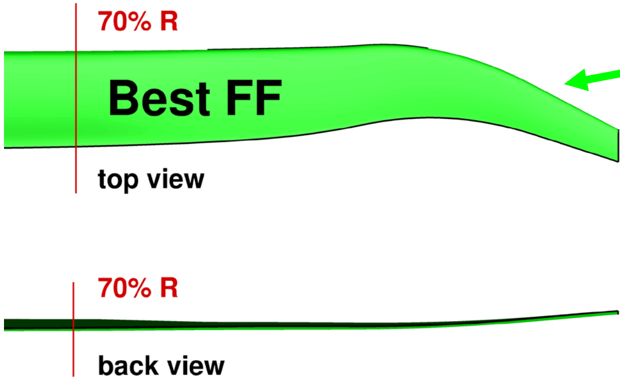




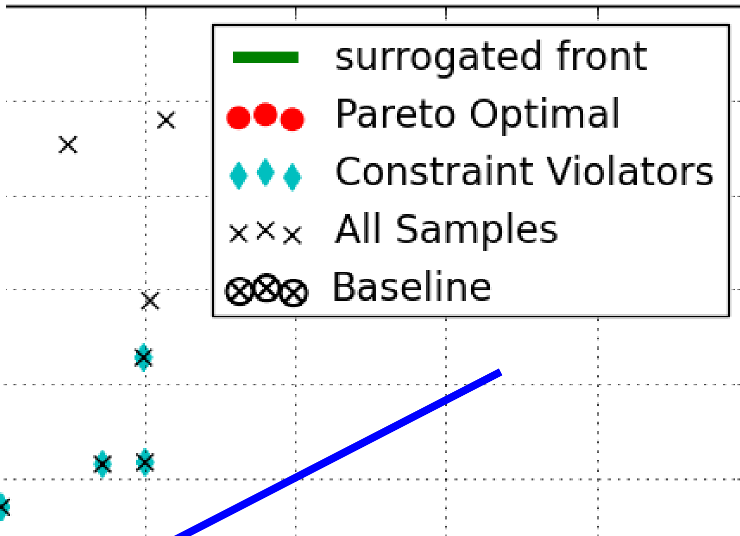
Simulation Fidelities:

	Low	High
Hover	Euler	RANS
Cruise	Prescribed Wake	uRANS

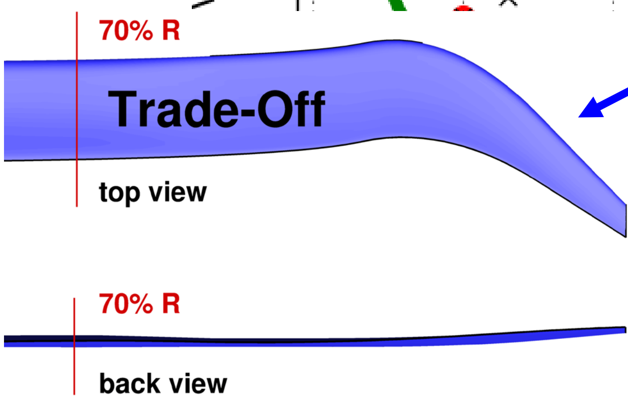
Multi-Point Rotor Optimization with 10 Design Variables



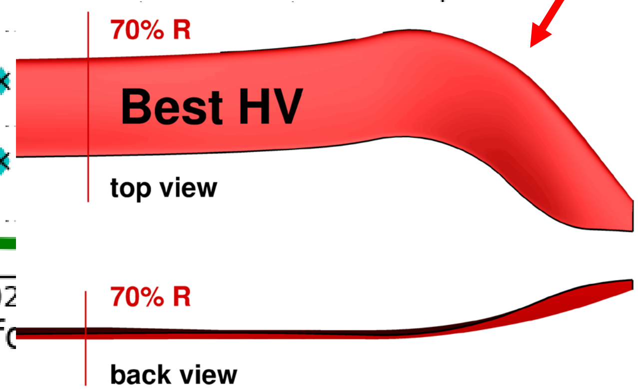
Required power	Forward	Hover
	-5.9 %	+30.7%
Overflight noise: -3.3 dB		



450 LoFi samples
150 HiFi samples



Required power	Forward	Hover
	-2.4 %	-2.0%
Overflight noise: -1.1 dB		



Required power	Forward	Hover
	+8.0 %	-6.5%
Overflight noise: +9.5 dB		

Helicopter fuselage drag reduction

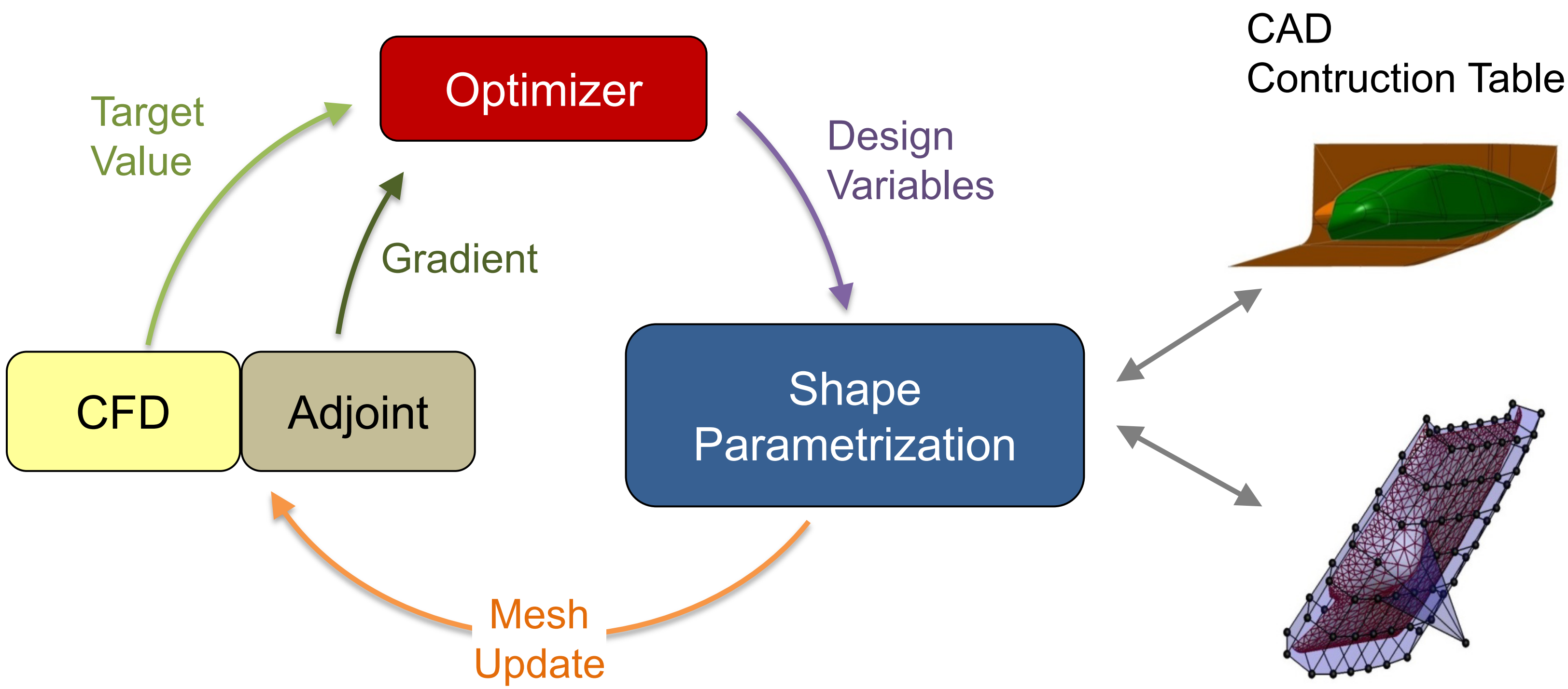
- shape of fuselage is defined by functionality (backdoor, radome, winch, etc…)
- large count of design variables and geometrical constraints
- Single design point

⇨ **gradient based optimization using adjoint**

back door

sponson

Adjoint based optimization process

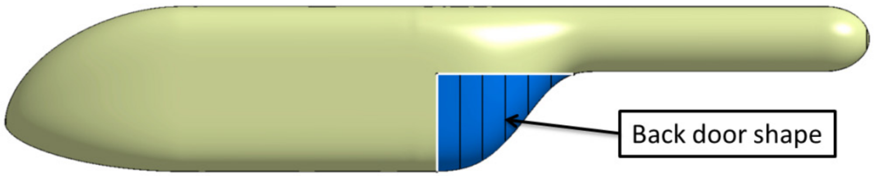


Optimization method:

- DLR’s RANS solver TAU (CFD and Adjoint)
- Line Search Algorithm with Conjugate Gradients

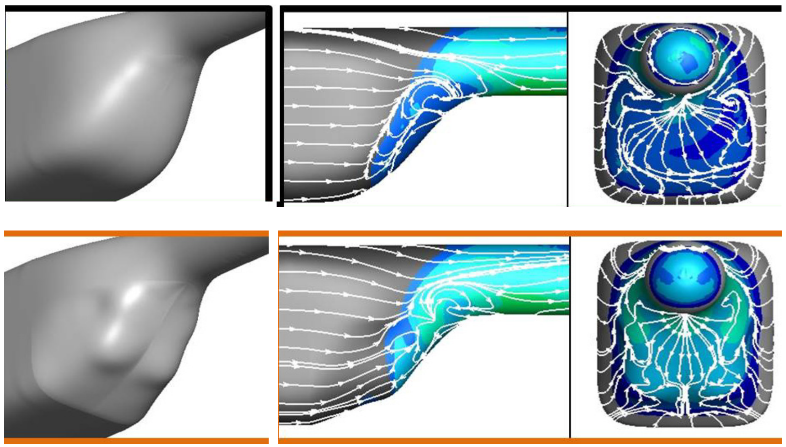
Adjoint based Fuselage Optimization
Application Examples

Fuselage of Robin-Mod-7 geometry

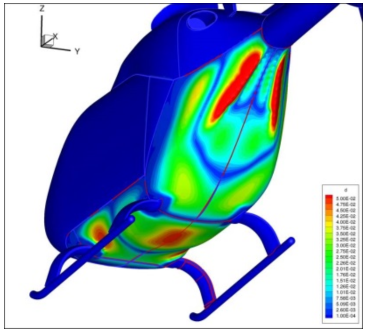


Baseline

CAD
21.8 %



Airbus Helicopters
“Bluecoper” Demonstrator



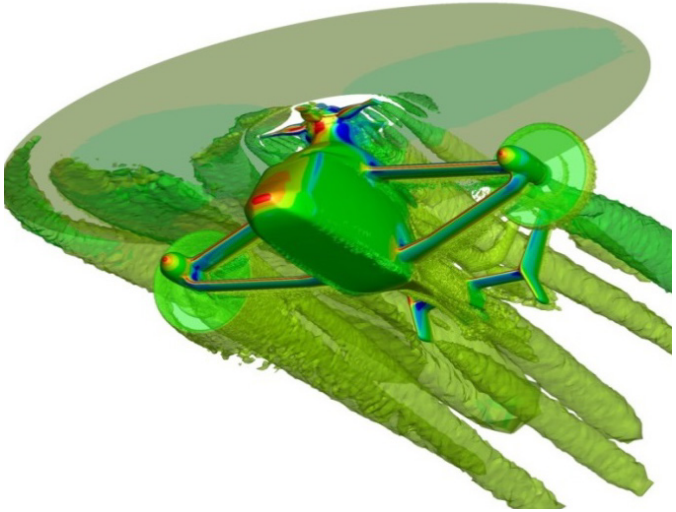
left: Initial EC135 back door design by DLR
right: final Bluecopter design

DLR

Design of fast rotorcraft

- The maximum speed of conventional helicopters about 150 kts = 280 km/h
- Airbus Helicopters develops the compound helicopter **“RACER”**
    - speed: 220 kts = 400 km/h
    - first flight expected for 2020
    - development within European funded Clean Sky 2 Project
- DLR and ONERA are partners in the aerodynamic and aeroacoustic design of RACER
    - first publications at the AHS- and ERF forum 2018 expected

RACER



DLR-Simulation

Outline

- Helicopter Research at DLR
- Numerical Simulation of Helicopter Aerodynamics
- Numerical Optimization of Helicopters
- **Helicopter Low Noise Flight Procedures**
- Measurement Techniques for Helicopters
- Wind Turbine Simulation
- Conclusion

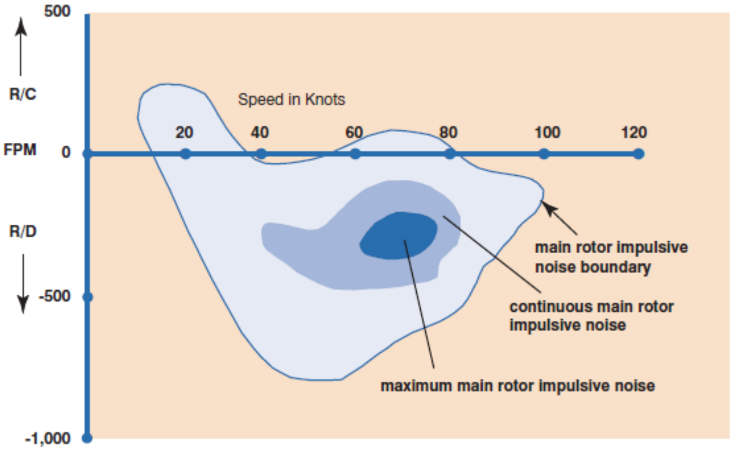
Noise Abatement Flight Procedures

Helicopter Noise has an important impact on public acceptance of helicopers
- criterion for certification
- stringent noise regulations for urban heliports

Two possibilities exist to reduce noise
- new helicopters: low noise design
- existing helicopter fleet: Noise abatement flight procedures

Noise abatement flight procedures
- avoid flying over noise sensitive (residential) areas
- avoid noisy flight states

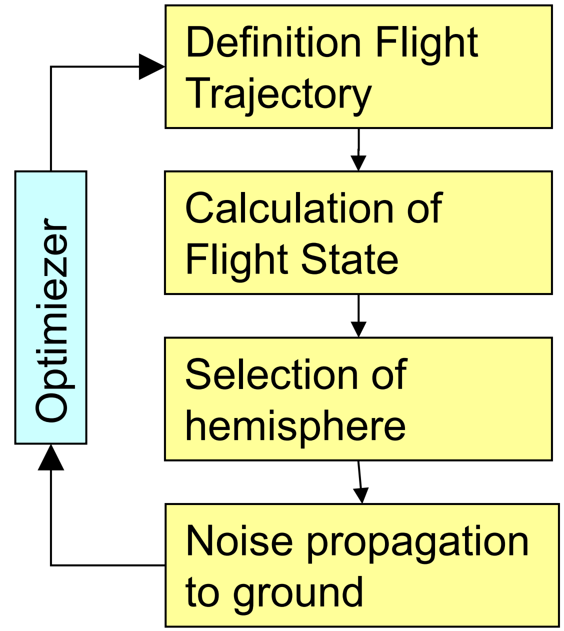
⇒ Optimization method needed

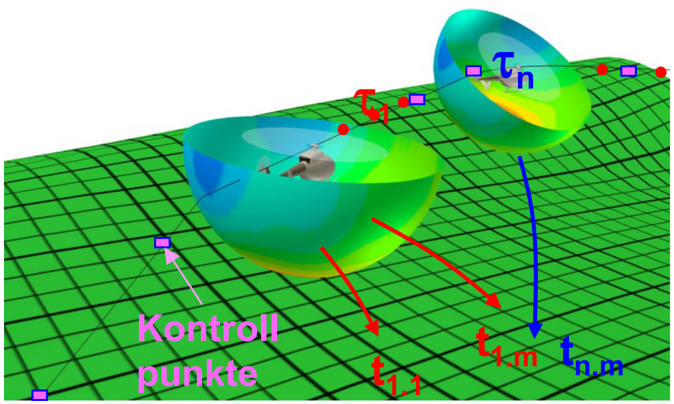


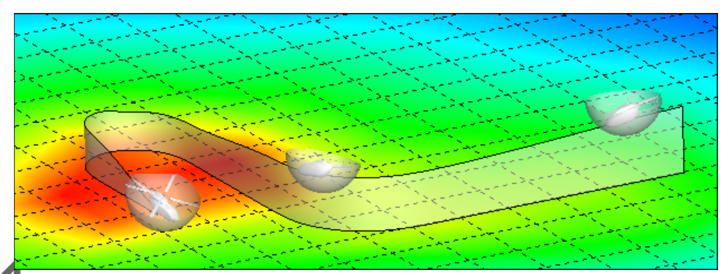
„fried egg"-plot of noise emission
(Source: Fly Neighborly Guide, HAI)

Optimization of Noise Abatement Flight Procedures

- DLR tool chain „SELENE“ for the Optimization of noise abatement flight procedures
- Objective function: reduction of noise imact
- Tool Chain based on large data base with Hemispheres representing noise characteristics

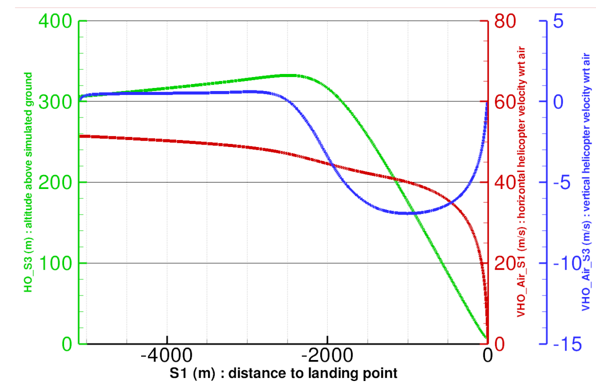






Left: prediction of noise emission

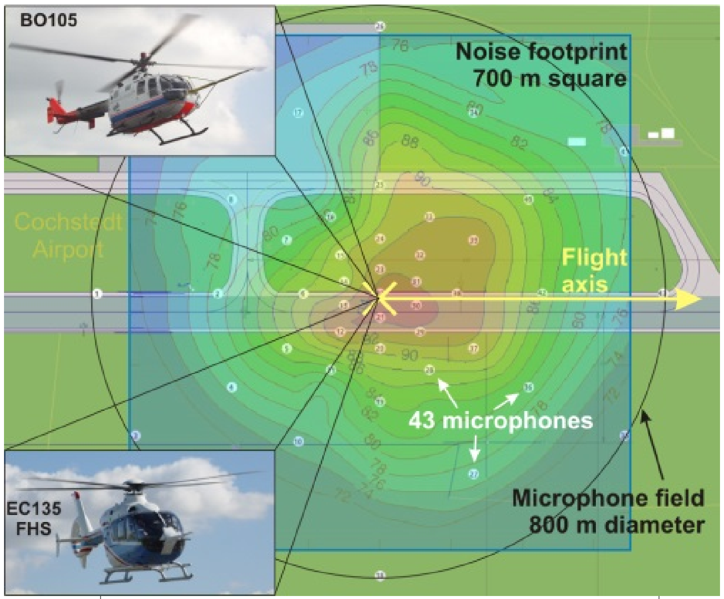
right: optimized flight trajectory

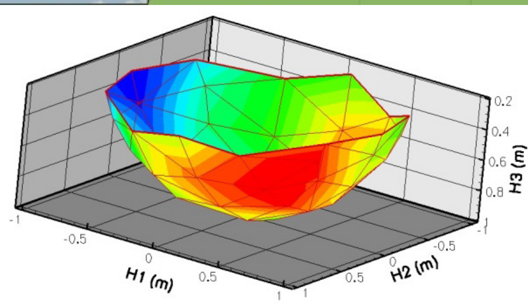


Derivation of Hemispheres

Extensive Flight experiments

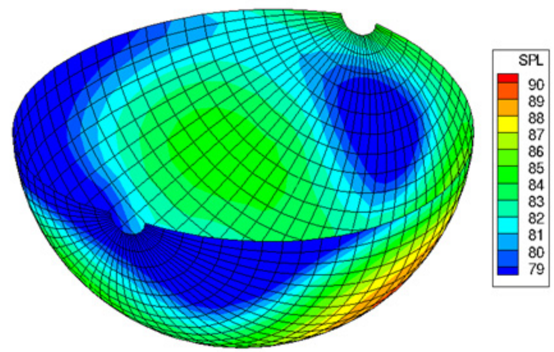
- 43 microphones over a 700 m diameter disk for capturing of noise directivity

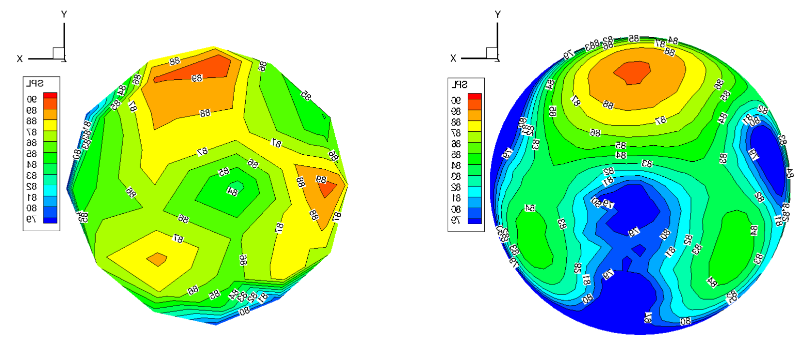




Numerical prediction

- significantly reduced effort
- but may miss certain noise features due to insufficient modelling



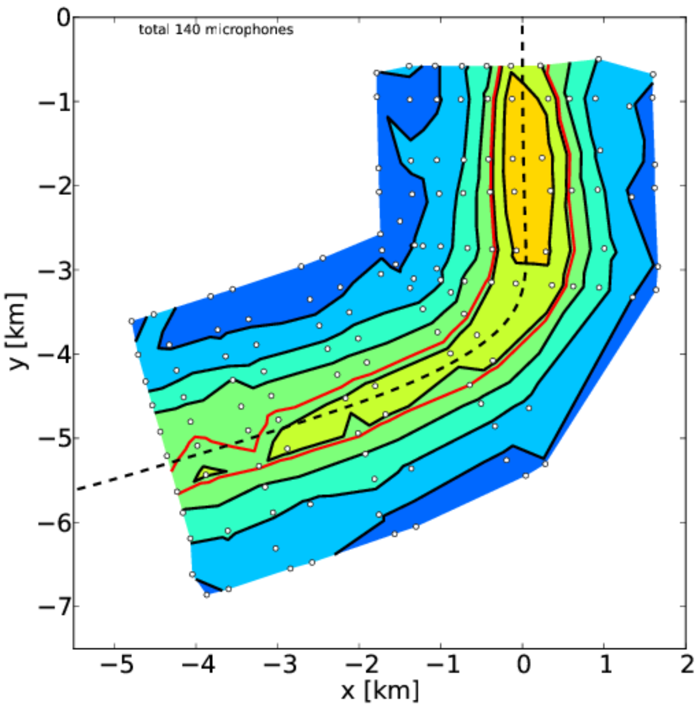


exp 55 kts num

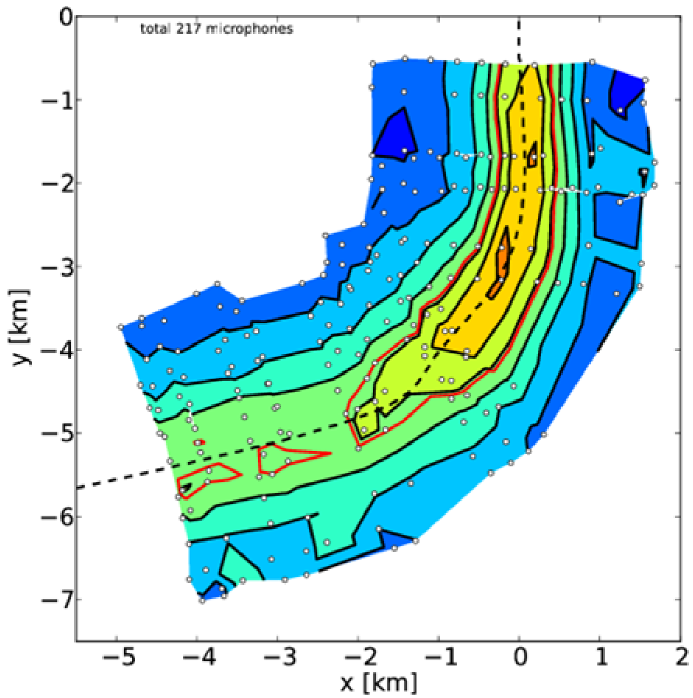
Flight Test result with EC135

- Area reduction inside red contour of 13%

Reference trajectory



Optimized trajectory



„Tunnel-in-the-Sky“ Display

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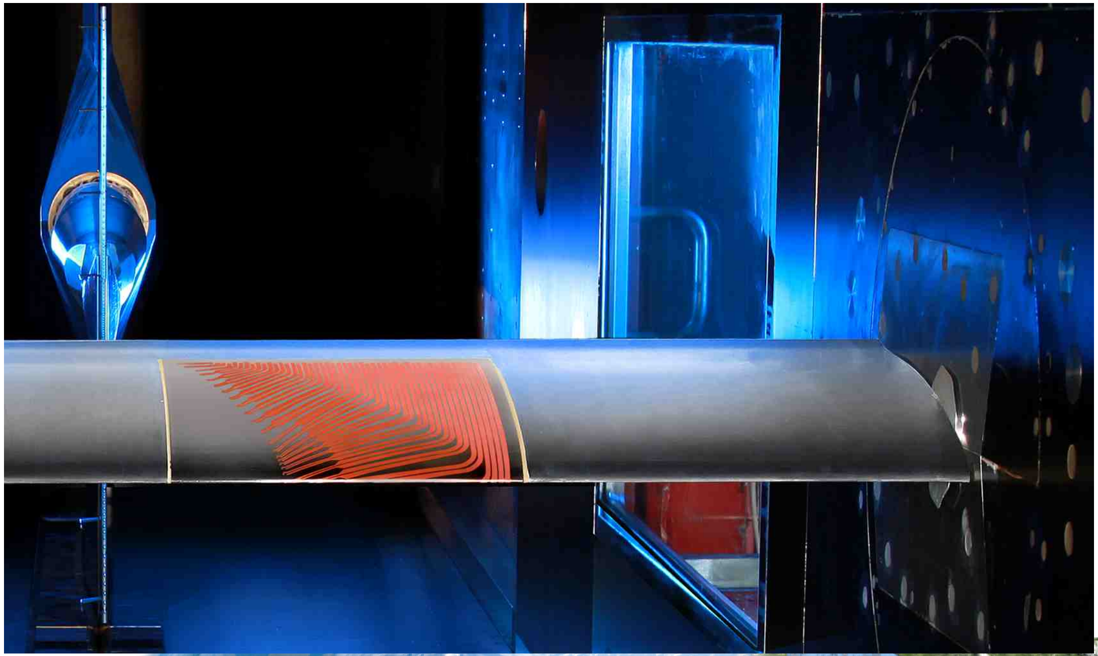
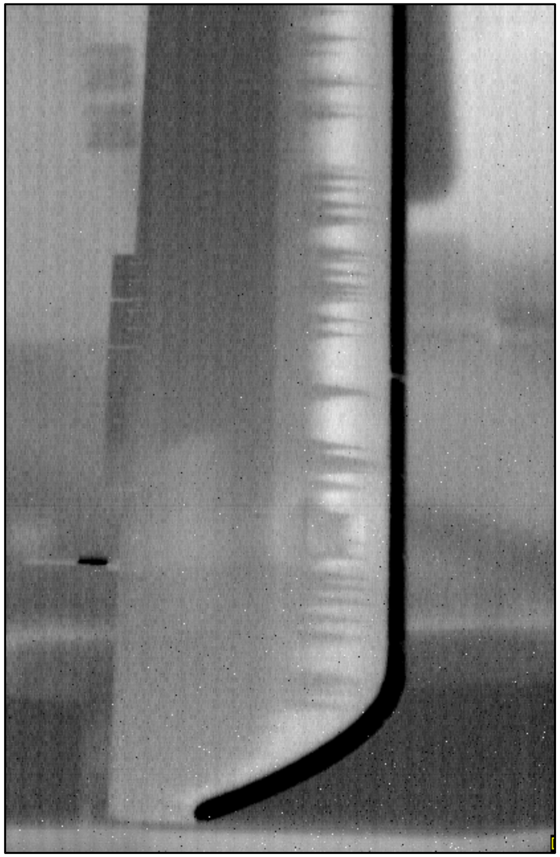
- Helicopter Low Noise Flight Procedures
- **Measuring Techniques for Helicopters**
- Wind Turbine Simulation

Airfoil-Testing in DNW-TWG Wind Tunnel

- Validation of helicopter airfoil design by wind tunnel experiments
- Model with 30 cm chord (= scale 1)
- equipped with sensors for pressures, forces and accelecations, hot film sensors for transition detection
- Particle Image Velocimetry (PIV)
- Pressurized Wind Tunnel allows for realistic Mach and Re
- unsteady Airfoil pitching with realistic frequencies and amplitudes



IRT measurements on a full scale helicopter rotor



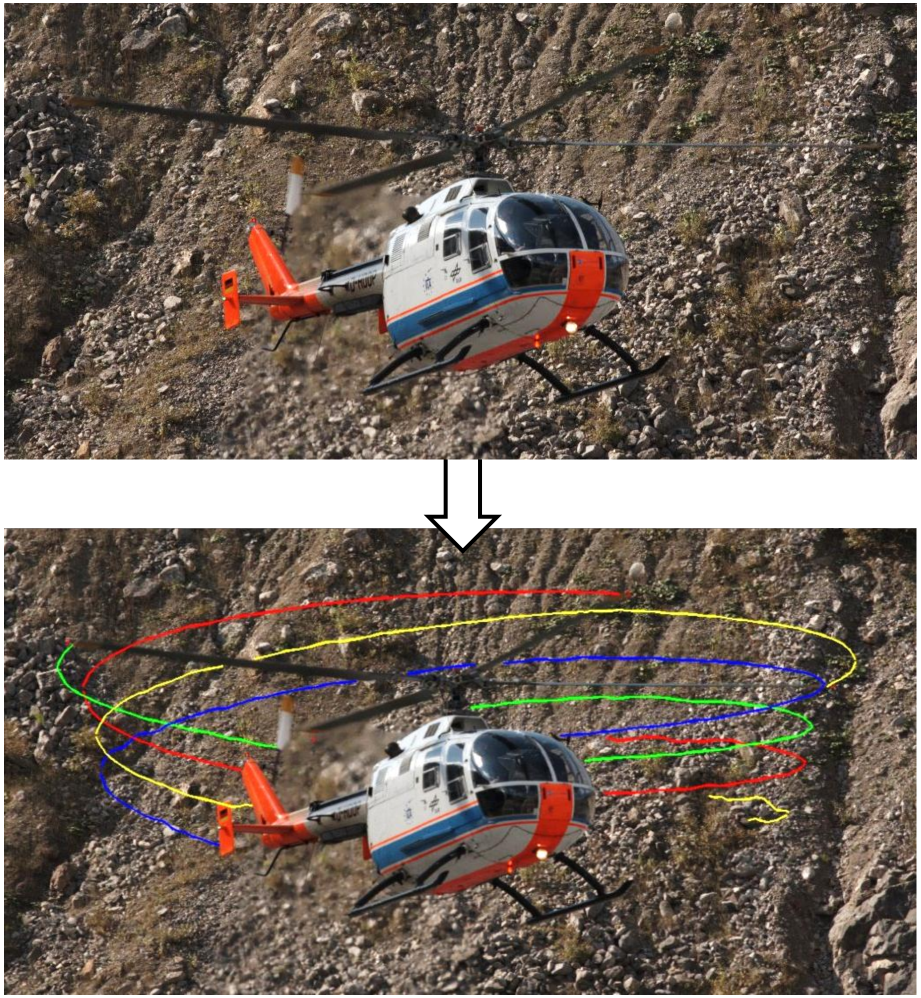
- DLR research helicopters EC135
- 4-bladed rotors, R ~ 5m, vtip = 211m/s (EC135)
- HSIR camera installed in building next to taxi way, 7.5m distance to blade tip
- Ground runs with zero thrust, hover IGE case

DLR

Backward Oriented Schlieren Technique

BOS detects density gradients from differences of two photos

- Acquisition of undisturbed reference and measurement image
- Mapping of images to compensate for eventual misalignments
- Stepwise cross-correlation between images
- Semi-automatic 2D vortex extraction and spline fitting



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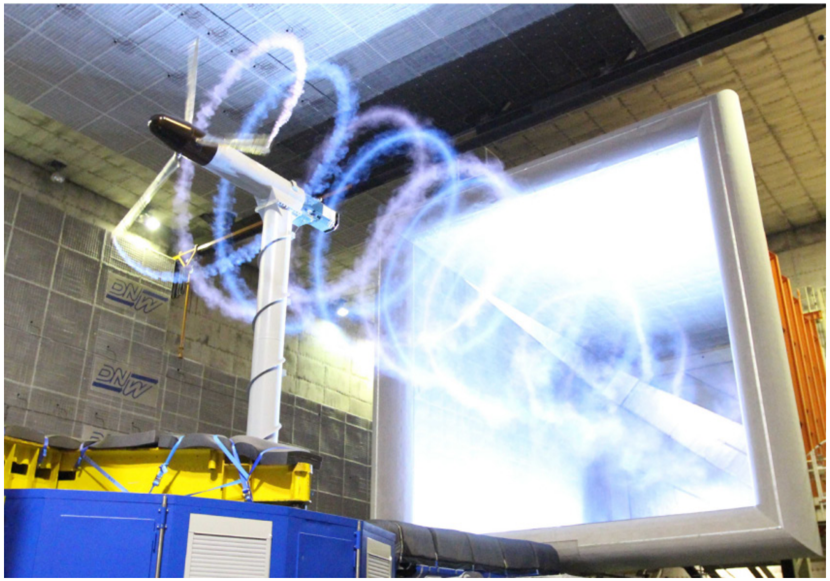
- **Wind Turbine Simulation**

Validation of TAU for Wind Turbine simulation

International MEXNEXT-Workshop

- Workshop to validate tools for aerodynamic predictions and to research aerodynamic phenomena
- Organized by International Energy Agency (IEA)
- 18 Participants from 10 nations

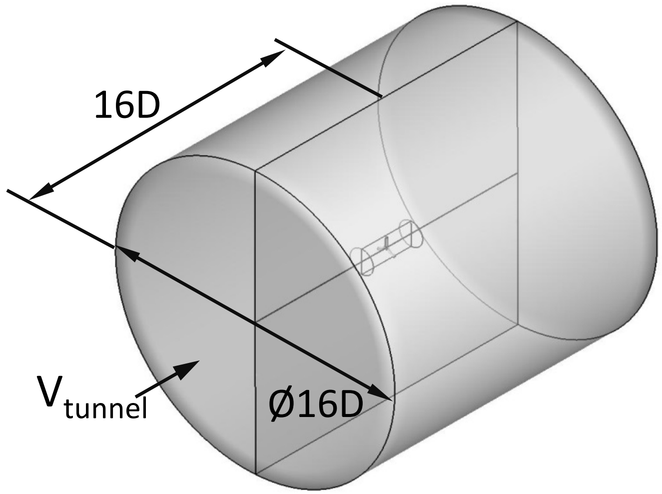


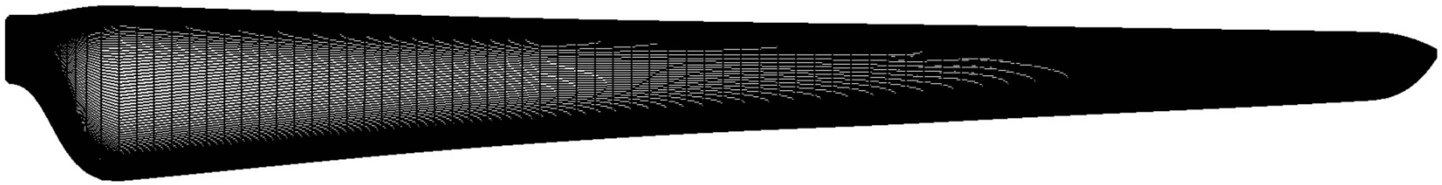
Test Case:

- MEXICO-rotor
- 4,5 m rotor diameter:
- tested in DNW-LLF 9.5 x 9.5m² wind tunnel
- very compete experimental data base

MexNext – Mesh

Grid dimensions:



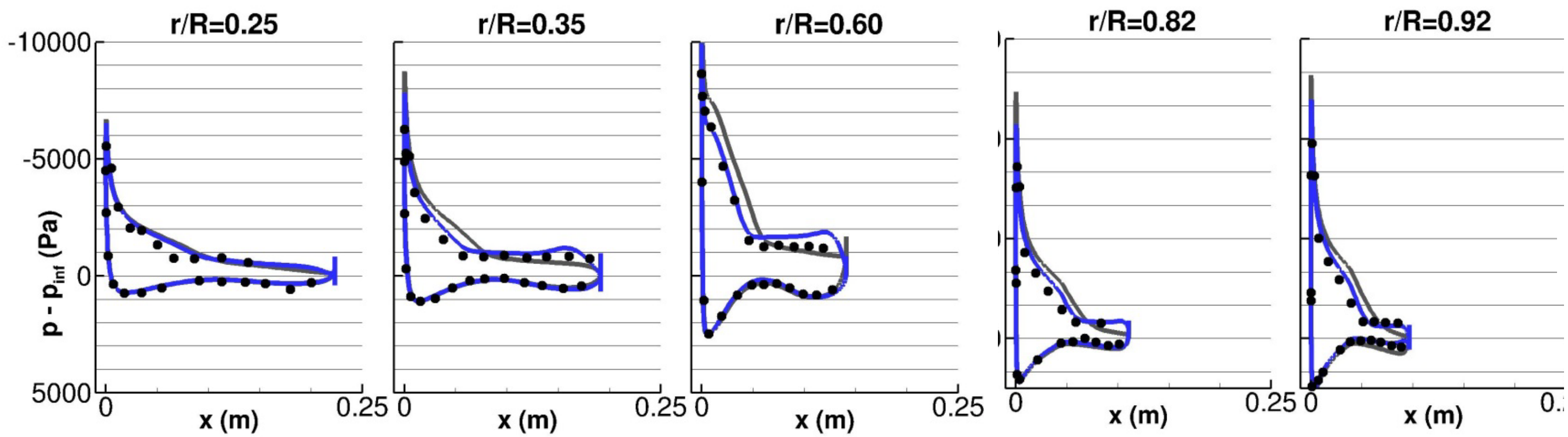


Total: 29 Mio. pts

Overset grid (hybrid): Cylindrical background + 3 x blade grids

MexNext TAU CFD simulations – Results

V_{tunnel}=24.05 m/s



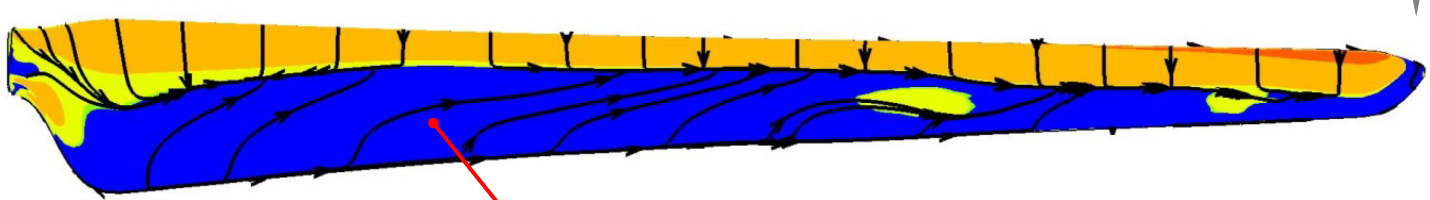
Wilcox-kω

Menter-SST

Exp.

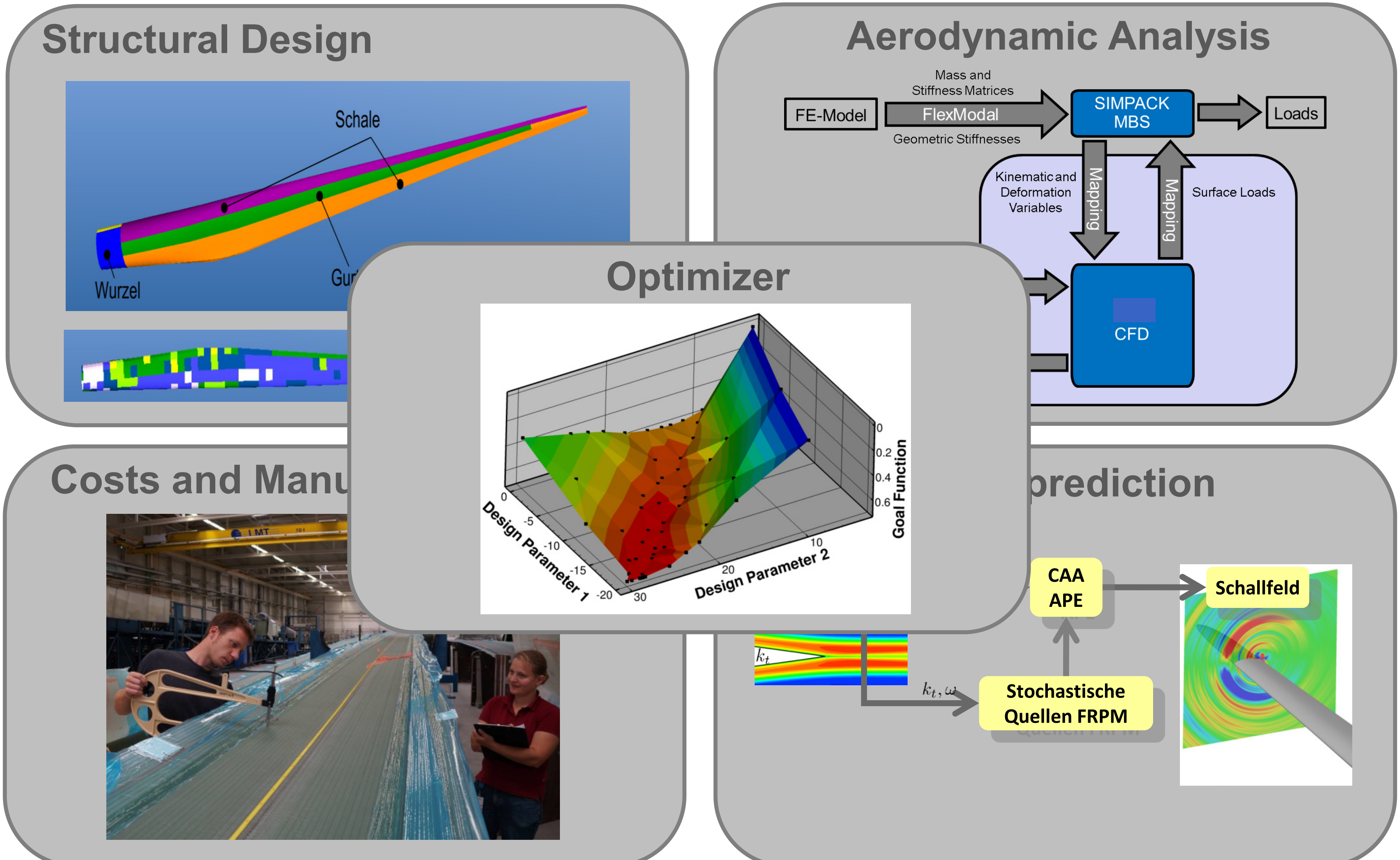
V_{tip}

Menter-SST
Suction side



separated flow area

Tool chain for Wind Turbine Design and Analysis

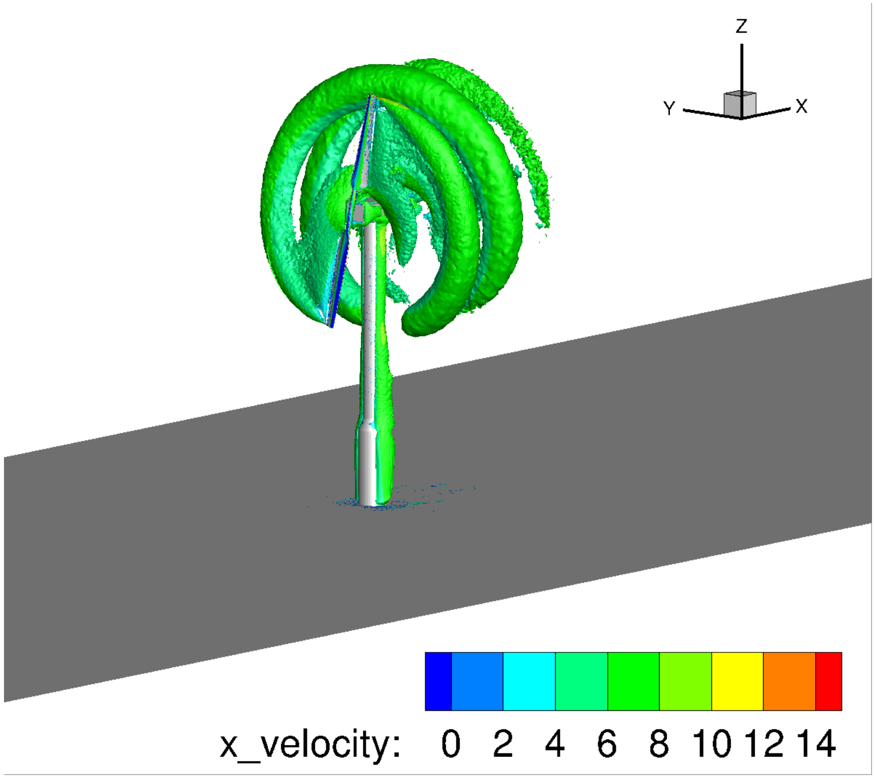


CFD solver THETA for Wind Turbine Aerodynamics

- Flow about wind turbines is incompressible
- incompressible CFD solvers advantageus
    - better accuracy
    - reduced simulation time

⇒ apply DLR's CFD solver THETA

- THETA is variant of TAU for incompressible flow
- originally developed for combustion
- significant enhancements for wind turbine applications (overset grids, transition prediction, …)
- supported by extensive validation



Conclusions

- Rotorcraft research at DLR covers a wide range of disciplines to make helicopters better performing, more passenger friendly with reduced environmental impact
- High effort required to develop tools for helicopter aerodynamics and acoustics
- Optical measurement techniques will provide further inside into aerodynamics
- Wind Turbine simulations benefit from synergies with Helicopters but require specific knowledge and effort
- Availability of good validation data critical
- DLR clearly benefited from co-operative research with JAXA

Outlok:

- Validation of TAU and acoustic tools for complete Helicopters in free flight
- Optimization of Helicopter rotors including noise and improved structural modelling

- Trilateral cooperation DLR-JAXA-ONERA on rotor optimization foreseen

DLR

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